Cone Beam Computed Tomography in Evaluations of Some Side Effects of Orthodontic Treatment

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To Anna, August,
Ann-Britt and Nils

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Abstract

In the late 1990s a new imaging modality, Cone Beam CT (CBCT) that enables high quality three-dimensional imaging at lower doses than Computed Tomography (CT), was introduced in dento-maxillofacial imaging.

In 2005 the Swedish Council on Health Technology Assessment (SBU), in a review of scientific articles on Malocclusions and Orthodontic Treatment in a Health Perspective, found low or contradictive evidence for an association between orthodontic treatment and risks for negative side effects. It was apparent that some of the issues raised only could be addressed by the use of a radiographic technique enabling three-dimensional imaging with high accuracy and reproducibility.

A new medical technology needs to be evaluated before implemented in research. This was the aim of two initial studies that, *in vitro*, examined the accuracy and precision in CBCT imaging using a Plexglas® object and a dry human skull and, *in vivo*, assessed its reproducibility in 13 patients. The results showed small differences between actual values and those obtained from measurements in CBCT tomograms and high reproducibility in measurements of root lengths and marginal bone levels.

A prospective radiographic study aimed to investigate root resorption and marginal bone level alterations during orthodontic treatment was conducted on 152 adolescent patients with a common type of malocclusion. CBCT examinations were made before (Baseline) and after treatment (Endpoint) and, in a randomly chosen group of 97 patients, six months after treatment initiation.

Root lengths, from those of incisors to those of first molars, and the marginal bone height at root surfaces around the teeth were measured in multiplanar reconstructed tomograms. The results showed that 95% of the patients had at least one tooth with a root resorption >1mm. Maxillary lateral incisors and premolars were most often affected and showed the most severe resorptions. Resorptions were also found at buccal and palatal root surfaces, only accessible with a tomographic technique. Jaw, tooth group, and root length at the six-month examination were significantly associated with the degree of root resorption at Endpoint.

Before treatment start, large differences in marginal bone height were found, particularly between tooth surfaces. At the end of treatment large changes in bone height among teeth and tooth surfaces could be seen. The largest changes were found at lingual and buccal surfaces, that is, surfaces that cannot be evaluated in conventional radiographs. In contrast, proximal surfaces at posterior teeth, hitherto subjected to most research, showed only small changes. The decrease of marginal bone height was larger in the mandible than in the maxilla and larger in girls than in boys, with respect to palatal/lingual surfaces.

A high quality CBCT technique is well suited for research on root resorption and marginal bone level changes during orthodontic treatment as it provides access to anatomic structures that cannot be evaluated in conventional radiographs, high measurement accuracy and precision, and possibilities to reconstruct images to compensate for changes in tooth/root positions that occur during orthodontic treatment.

Keywords: Cone beam computed tomography, orthodontics, adolescents, root resorption, marginal bone height

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Contents

Preface

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

I Lund H, Gröndahl K, Gröndahl H-G.
Accuracy and precision of linear measurements in cone beam computed tomography Accuitomo® tomograms obtained with different reconstruction techniques.
Dentomaxillofacial Radiology 2009; 38:379-386

II Lund H, Gröndahl K, Gröndahl H-G.
Cone beam computed tomography for assessment of root length and marginal bone level during orthodontic treatment.
Angle Orthodontist 2010; 80:466-473

III Lund H, Gröndahl K, Hansen K, Gröndahl H-G.
Apical root resorption during orthodontic treatment: A prospective study using cone beam CT.
Angle Orthodontist 2011;doi: 10.2319/061311-390.1

IV Lund H, Gröndahl K, Gröndahl H-G.
Cone beam computed tomography evaluations of marginal alveolar bone before and after orthodontic treatment.
European Journal of Oral Sciences. Submitted September 2011

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Introduction

General background

The results of an ad-hoc review group appointed by the Swedish Council on Technology Assessment in Health Care to study Malocclusions and Orthodontic Treatment in a Health Perspective (Bettavvikelser och tandreglering i ett hälsoperspektiv, SBU 2005)[1] became the impetus for this study in that one of the goals of the review group was to determine the scientific evidence of an association between orthodontic treatment and risks for unintentional negative effects. The review group concluded that the scientific evidence with respect to the side effects of orthodontic treatment in several aspects was low or contradictive.

Several requirements must be met when high evidence studies are to be performed in e.g. orthodontics. When the results are based on radiographic data these must be valid, accurate and precise. Cone beam computed tomography (CBCT) may offer better possibilities than previous radiographic methods to evaluate different aspects on orthodontic treatment, including adverse side effects.

Cone beam computed tomography

Although originally developed in the beginnings of the 1980s at the Mayo Clinic Biodynamics Research Laboratory (Robb 1982) for studies of cardiac and pulmonary functions, cone beam computed tomography (CBCT) became available for dento-maxillofacial imaging in the late 1990s as a result of an evolution in computer science (Mozzo et al. 1998, Arai et al. 1999).

CBCT is a generic term for a technology comprising a wide variety of machines differing from each other in many respects. The principle behind the technique is that a cone-shaped x-ray beam makes a circular movement around the patient with the center of the circle positioned either in the midpoint of the head, the jaw/s, or a specific region of interest. To lower the radiation dose to

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1 http://www.sbu.se/upload/Publikationer/Content0/1/Fulltext_tandreglering.pdf

the patient the aperture through which the radiation exits the x-ray tube is in the form of a square or rectangle making the circular base of the cone become of the same shape. The size and shape of the primary aperture determine the size of the cylindrical tissue volume that becomes irradiated – the field-of-view (FOV). On the opposite side of the x-ray tube a detecting device is found. The x-ray tube and the detector are mechanically connected by means of a horizontal, or vertical, gantry, the former for sitting or standing patients, the latter for patients in a supine position. During the rotation the exposure is either continuous or pulsed, synchronized with the data acquisition. In both cases multiple 2-dimensional image data sets are collected by the detector and transferred to a computer where volumetric data are produced during a so-called primary reconstruction. The data can then be visualized as 2-dimensional multiplanar reformatted scans or in a 3-dimensional format by segmentation of the data set and surface reconstruction – so-called volume rendering (Scarfe & Farman 2008). The unit element of the image volume is the voxel (volume element), the size of which has a determining influence on the spatial resolution. The contrast resolution depends on the number of gray-levels that each voxel can attain, often described as the so-called bit-depth, since the number of gray levels usually is described as 2 raised to the power of a specific number. For example, in an image with bit-depth 6, the voxel can attain $2^6 = 64$ gray levels, in one with bit-depth 12 it can attain $2^{12} = 4\,096$ gray levels.

The CBCT technique makes it possible to obtain thin tomographic images in any direction increasing the possibility of investigating bone levels and root surfaces not visible in conventional radiographs. Also, its ability to create scenes similar to previous ones, despite changes in tooth/root positions as a result of orthodontic treatment, ensures that identical anatomical structures can be compared over time.

CBCT should not be considered a variant of Computed Tomography (CT) (Molteni 2008). The use of the term CT is occasionally seen, when CBCT is meant, but this ought to be discouraged. To avoid any confusion with CT or MSCT (multi-slice CT), the expressions DVT (digital volume tomography) and DVI (digital volume imaging) and several others have been suggested.

CBCT and radiation doses

The radiation dose to the patient varies between machines depending on type of exposure (continuous or pulsed), kV, filtration, mA, rotation time, and the field-of-view (FOV). Some units allow the FOV to be selected to suit the purpose of the examination, ranging from small FOVs for dental imaging to large ones for maxillo-facial examinations. Among others, Pauwels et al. (2010) have demonstrated how the effective radiation dose varies between CBCT units. In Table 1 effective doses for some CBCT units are found together with effective doses for some other types of techniques for maxillofacial radiography.

Table 1. Effective doses associated with dental imaging modalities. Effective dose data (ICRP 103) derived from: Garcia Silva et al. 2008, Hirsch et al. 2008, Ludlow et al. 2008, Ludlow & Ivanovic 2008, Silva et al. 2008, Loubele et al. 2009, Okano et al. 2009, Roberts et al. 2009, Suomalainen et al. 2009, Pauwels et al. 2010, Qu et al. 2010

Modality	Effective dose range (mSV)
Intraoral radiography*	
Single radiograph	<0.002
Full mouth survey (20 radiographs)	0.035-0.040
Panoramic radiography	0.003-0.024
Lateral (Ceph) radiography	<0.006
Cone beam CT	
Dento-alveolar**	0.019-0.674
Craniofacial***	0.030-1.073
CT, MSCT	0.280-1.410

* F-speed film or photostimulable phosphor plate with rectangular collimation
** FOVs < 10cm in height
*** FOVs > 10cm in height

CBCT in orthodontics

Over the past decade CBCT has become a frequently used radiographic technique in orthodontic treatment planning and monitoring (Kau et al. 2005), particularly in North America. The American Association of Orthodontists recently adopted a resolution stating that while the organization recognizes "that there may be clinical situations where a CBCT radiograph may be of value, the use of such technology is not routinely required for orthodontic radiography" (American Association of Orthodontists, Resolution 26-10H, 2010).[2] The British Orthodontic Society in their Guidelines to Orthodontic Radiographs recommends orthodontists to use CBCT with caution and emphasizes that its routine use cannot be justified (Isaacson et al. 2008).

An historical perspective on orthodontics

Orthodontics has been an integral part of dentistry for thousands of years (Asbell 1990). The development of the first known orthodontic appliance is attributed to Pierre Fauchard (1678-1761), who in 1723 designed a so-called bandolet aimed to expand the dental arch, particularly its anterior part. Pierre Fauchard in 1728 published a two-volume book *Le Chirurgien Dentiste* that became the advent of dentistry based on fundamental knowledge, today called evidence. He is, therefore, often referred to as the "Founder of Modern Dentistry". In his orthodontic treatment he rarely performed extractions of permanent teeth. Etienne Bourdet (1722-1789), who was the dentist to the King of France and also performed orthodontics, recommended the Fauchard method but, in contrast to Fauchard, advocated the extraction of the first premolars to preserve symmetry of the jaws.

In principle, although not in its details, modern orthodontic treatment has much in common with that earlier practiced, in that it may combine orthodontic tooth movement with tooth extractions.

One can assume that in historic times orthodontic treatment was reserved for the few and rich. Gradually it has become a treatment for the many. Today, in the industrialized world, not least in countries where dental treatment for the young is free or heavily state subsidized, those in need of orthodontic treatment will receive it. In the Nordic countries between 11% and 35% of all children and adolescents are orthodontically treated (Mohlin et al. 2007a) with an average of 27% in Sweden (21%-39%, depending on county). In Germany around 34% of all children are orthodontically treated (Krey & Hirsch 2011). Thus, with the exception of prevention and treatment of dental caries, orthodontic treatment seems to be the most common dental treatment among children and young teenagers in these parts of the world. This is also reflected in the number of orthodontic specialists. In Sweden 31% of all licensed specialists within dentistry are orthodontists making orthodontics the largest dental specialty. By comparison, 17% are oral surgeons and 11% are pedodontists

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2 http://www.aaomembers.org/Resources/Publications/ebulletin-05-06-10.cfm

(Swedish National Board of Health and Welfare 2010).[3] The highest ratios of orthodontists in relation to population (per 100 000 inhabitants) are found in North America, Central and South America, and Europe (1.4 to 2.6) according to the World Federation of Orthodontists.[4]

In the perspective of the large number of people who receive orthodontic treatment today and the expected increase in the number of patients who will receive it in the future, economic resources permitting, the prevalence and severity of possible adverse side effects to orthodontic treatment become an important issue.

Side effects of orthodontic treatment as described to potential patients

All medical and dental treatment procedures are associated with risks of side effects of varying degree and severity. Orthodontic treatment is no exception. An Internet search for *"Side effects of orthodontic treatment"* in August 2011 gave 6 990 hits. One of the longest lists of possible side effects was found in a patient consent form from the Department of Orthodontics, the Dental School at the University of Washington, Wash, U.S.A.[5] An excerpt of this is found below:

"Although infrequent, these potential risks must be taken into consideration when deciding to undergo orthodontic treatment:

- *Having braces or other orthodontic devices in your mouth can increase the amount of plaque, bacteria and food that gets trapped around your teeth.*
- *Poor brushing and flossing may result in puffy, infected gums.*
- *A diet high in sugar can result in permanent white decalcifications or "enamel scars". These white spots can progress to tooth decay.*
- *…*
- *Some patients experience some shortening of the tooth roots while their teeth are being moved. This shortening, called "root resorption", is usually minimal and has no serious consequence. The risk of root resorption is greatly reduced in limited treatment.*
- *There can be loss of the supporting bone or gum tissue if treated teeth are infected or experiencing active periodontal disease.*

3 http://www.socialstyrelsen.se/publikationer2010/2010-10-4

4 http://www.wfo.org/archive/gazette/20000502/Gazette/study.htm

5 http://courses.washington.edu/predoc/Ortho631/Clinical Arm Homepage/Helpful Documents/ConsentLtdOrtho.pdf

- *…*
- *Occasionally, patients develop discomfort in the muscles of the face or the temporomandibular joints (TMJs).*
- *…"*

In the introduction to this consent form it is stated that negative side effects of orthodontic treatment are rare and not usually very severe. Also, in the majority of the Internet sites directed to potential patients the negative side effects are described as limited. Typical examples are:

- *There are few risks or side effects to orthodontic treatment. The few problems that do occur are most often because the patient did not follow the advice of the dentist or orthodontist.*[6,7]

- *Mild loss of tooth root tissue (dissolving) is very commonly seen as a consequence of tooth movement but this does not cause any long-term problems for the vast majority of patients.*
If a patient's oral hygiene is poor during treatment, orthodontics may exacerbate gingival inflammation and susceptibility to periodontal (gum) disease. Patients who have undergone orthodontic treatment do not have any increased pre-disposition to developing periodontal disease.[8]

- *Root resorption is a shortening of the tooth roots. It can occur with or without orthodontic appliances and it is very difficult to forecast susceptibility to this condition. Some orthodontic patients are predisposed to this problem, while most are not. Very slight changes in root length are normal in orthodontic treatment and are usually insignificant; they cause no long-term ill effects in a healthy mouth.*[9]

- *Gingivitis is the inflammation (redness and swelling) of the gum tissue, while Periodontitis is the actual breakdown of the gum and bone surrounding the teeth. The fact is GINGIVITIS HAPPENS … **except** in the cases where patients maintain impeccable oral hygiene. Periodontitis tends to be an individual reaction to certain types of bacteria that reside in the mouth; hence some patients are more predisposed than others to this breakdown of the periodontal tissue. Again, maintaining immaculate oral hygiene greatly reduces the chances of development or progression of gum disease.*

6 http://www.cdaadc.ca/en/oral_health/procedures/orthodontics/index.asp
7 http://www.aquariusdental.com/dental-services/orthodontics/things-to-consider/
8 http://www.hereforddentist.co.uk/blog/tag/uk-orthodontist/
9 http://www.braceplace.co.uk/Are_there_any_side_effects_or_problems.htm

Commonly, the root-tips of some teeth shorten (or resorb) during treatment. However, as long as the patient maintains dental health, a small amount of root resorption will not affect their overall oral health. If the condition becomes severe (a rare occurrence), Orthodontic treatment may have to be discontinued before it is completed.[10]

In general, side effects of orthodontic treatment in terms of root resorption are described as insignificant. Effects on marginal bone levels are rarely mentioned. When they are, they are ascribed to the patients' failure in following the advice of the dentist/orthodontist. In a great many sites directed toward potential patients only one "side effect" is mentioned:

- An attractive smile is a pleasant "side effect" of orthodontic treatment.[11,12]

Side effects of orthodontic treatment in the scientific literature

It is well known that the biological tissue response to orthodontic treatment that enables teeth to be moved in the alveolar bone (Melsen 1999) also can cause adverse side effects on involved tissues. Different types of root resorption was discussed by Ottolengui already in 1914. Without actually relating apical root resorption to orthodontic treatment he describes its occurrence in some orthodontically treated patients.

Most research on orthodontic side effects has focused on the orthodontically induced inflammatory root resorption – OIIRR – (Brezniak & Wasserstein 1993a,b, 2002a,b, Weltman et al. 2010). Other side effects attributed to orthodontic treatment are higher incidences of caries and gingivitis due to the difficulties in maintaining a good oral hygiene in the presence of fixed orthodontic appliances (Øgaard 1989, Alexander 1991, Ristic et al. 2007, Richter et al. 2011). Less research has been directed towards adverse affects on the marginal bone level by the orthodontic treatment itself. In addition to being sparse the research on the effect of orthodontic treatment on the alveolar bone level has been limited to what occurs at mesial and distal aspects of the roots (Zachrisson & Alnaes 1974, Hollender et al. 1980, Aass & Gjermo 1992, Bondemark 1998, Janson et al. 2003). Orthodontic treatment has been linked to temporo-mandibular joint symptoms (Larsson & Rönnerman 1981, Nielsen et al. 1990) but recent research has found limited evidence for this connection

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10 http://www.islandsmiles.com/about_ortho-InformedConsent.htm

11 http://www.yarbroughortho.com/FAQ.html

12 http://www.mcsweeneyortho.com/Treatment/FullTreatment/tabid/185/Default.aspx

(McNamara 1997, Mohlin et al. 2007b). Furthermore, orthodontic treatment can cause pain related to the biological tissue response – an inflammatory reaction triggering various biochemical mediators (Krishnan 2007).

This thesis is concerned with two possible side effects of orthodontic treatment – apical root resorption and changes in marginal bone height – and how their prevalence and severity can be described by a novel radiographic technique. When the Swedish Council on Technology Assessment in Health Care (SBU) in 2005 presented the results of a review of the orthodontic literature the publications were graded according to scientific evidence (Table 2).

Table 2. Criteria used when judging the level of scientific evidence

Level	Criteria
High evidence	Randomized controlled trial Well-defined and adequate control group Well-defined parameters Reliability tests Low drop-out rate Relevant statistical analysis
Middle high evidence	Prospective study or well-defined retrospective study Well-defined parameters Low drop-out rate Relevant statistical analysis
Low evidence	Cross-sectional study High drop-out rate Lack of control group Limited statistical analysis

Regarding the risk for OIIRR, the SBU group of reviewers found eight publications out of 91 that met the criteria for middle high evidence, but none that met those for high evidence. The eight publications were: DeShields (1969), Goldson & Henrikson (1975), Odenrick & Brattström (1983), Beck & Harris (1994), Hendrix et al. (1994), Blake et al. (1995), Taithongchai et al. (1996), and Mavragani et al. (2002). The main reasons for excluding articles concerning OIIRR were that they were based on experimental, histological data, were review articles or that inadequate radiographic techniques had been used. With respect to marginal bone loss only three publications (Aass & Gjermo 1992, Bondemark 1998, Årtun & Grobety 2001) out of 27 met predefined criteria for high or middle high evidence. The main reasons for excluding publications regarding periodontal side effects were that too few patients had been studied, were adults, or that the treatment strategies were not up-to-date.

In respect to root resorption and marginal bone loss the SBU reviewer group came to the following conclusions:

- Root resorptions up to one third of the root length are found in 11% to 28% of patients who have been orthodontically treated.
- The long-term consequences of root resorptions are unknown.
- Teeth with incomplete root development show less root resorptions than teeth with complete root development.
- Prevalence and severity of OIIRR are independent of gender.
- Evidence for a correlation between OIIRR, age at treatment start, treatment time, tooth group or root anatomy is poor.
- No evidence exists for an influence of endocrine disorders, nutrition and hormonal imbalances, nor for trauma before treatment or various mechanical factors such as type of appliance and magnitude of applied force, factors discussed in a literature review by Brezniak & Wasserstein (1993b).
- Orthodontic treatment can cause a decrease of the approximal marginal bone level, but to an extent without clinical significance.

Methods to study apical root resorption

In most studies of OIIRR intraoral periapical radiography has been used (Brezniak & Wasserstein 1993a, 2002b). This technique has shortcomings (Brezniak et al. 2004a, Katona 2006, 2007, Dudic et al. 2008) even when efforts are made to obtain periodically identical radiographs (Chapnick & Endo 1989, Brezniak et al. 2004b, Katona 2006, Gegler & Fontanella 2008) or to compensate for image distortions by using mathematical algorithms (Brezniak et al. 2004c, Katona 2007). In an *in vitro* study Follin & Lindvall (2005) showed that resorptions on the buccal or palatal surface of the apical part of the root had to result in root shortening to become visualized in periapical radiographs.

Since teeth are moved, rotated and tipped during the orthodontic movement one cannot achieve identical irradiation geometry with standard radiological techniques. Therefore, it can be safely assumed that digital subtraction radiography for the study of OIIRR cannot be successfully applied.

In panoramic radiographs root apices, especially in anterior regions, can become placed outside the narrow focal trough. In orthodontic patients, specifically among pronounced Class II and III cases, and in patients with excessively proclined or retroclined teeth, it is not always possible to position both upper and lower front teeth within the focal trough (Leach et al. 2001). Sameshima & Asgarifar (2001) found that panoramic radiographs overestimated the amount of root resorption by 20% or more compared with periapical radiographs. The usefulness of lateral cephalometric radiography in detecting root resorption is limited due to super-impositioning of teeth (Leach et al. 2001). Therefore, studies based on this technique were excluded in the review by the Swedish Council on Technology Assessment in Health Care.

For more demanding tasks within dentistry, CT can be used, nowadays mostly in the form of multi-slice computed tomography (MSCT). However, in orthodontics the radiation exposure to the patient limits its use to complex maxillofacial malformations, such as different types of syndromes, and to treatment planning before advanced orthognatic surgery.

Regarding the use of CBCT in the diagnosis of orthodontically induced apical root resorption, Dudic et al. (2009) pointed out that its diagnostic ability has not been sufficiently studied.

Methods to study marginal bone level

The use of radiographic imaging as an aid in the diagnosis and treatment of periodontal disease is widely accepted (Mol 2004). Its main purpose is to assess the level of the marginal alveolar bone, including the pattern and extent of bone loss. Linear measurements from the cemento-enamel junction to the marginal bone crest, or to the most apical part of an osseous defect, are commonly used. Bitewing, periapical and panoramic radiography are the most frequently used techniques. All can provide important diagnostic information, but none are without limitations. Their main limitation is the difficulty in assessing the marginal bone level on the buccal and palatal aspects of the root. Therefore, bone level measurements are mostly limited to the proximal root surfaces. Generally, marginal bone loss is underestimated even in high quality radiographs (Lang & Hill 1977, Albandar & Abbas 1986, Albandar 1989, Åkesson et al. 1992). Benn (1990) remarked that accurate measurements of small amounts of marginal bone loss over time requires a monitoring system with small errors in determining the anatomical reference points. He concluded that intraoral radiography is not sensitive enough to measure true bone loss until at least 1.0mm of bone loss has occurred.

To overcome some of the limitations of the intraoral technique, digital subtraction radiography has been used for the diagnosis of marginal bone level changes (Gröndahl et al. 1983, Brägger 1988, Jeffcoat & Reddy 1993). In order for the technique to be useful it is imperative that the baseline projection geometry and image contrast can be reproduced at follow-up examinations (Gröndahl et al. 1984, Benn 1990). With the changes that occur during orthodontic treatment, the usefulness of digital subtraction for the detection of changes in the marginal bone level must be considered low.

Tuned aperture computed tomography (TACT®) has been tested for imaging of the alveolar bone and shown to improve the ability to detect osseous defects around teeth and implants (Webber et al. 1997). Results of studies testing TACT® and TACT® subtraction for detection and localization of osseous changes in the crestal bone are encouraging (Chai-U-Dom et al. 2002, Ramesh et al. 2002). The technique does not require standardization of the irradiation geometry (Webber & Bettermann 1999, Linnenbrügger et al. 2002) and radiation doses can be kept low since the dose required for each of the different projections can be kept so small that their sum total will not exceed that for an intraoral radiograph (Webber et al. 1997). No information can be found about the use of TACT® in the study of orthodontic side effects.

Studies have shown CT assessment of alveolar bone height and angular defects to be reasonably accurate and precise (Fuhrmann et al. 1995a, Fuhrmann et al. 1995b, Fuhrmann et al. 1997). However, both cost-benefit and cost-effectiveness ratios of CT imaging for periodontal diagnosis must be considered low due to high monetary costs and high radiation doses.

A few studies have used CBCT in studies of alveolar bone morphology *in vivo* (Rungcharassaeng et al. 2007, Gracco et al. 2009, Kim et al. 2009, Evangelista et al. 2010). Others have evaluated the CBCT technique by studying artificially created defects in human skulls (Mengel et al. 2005, Misch et al. 2006) or naturally occurring defects in dry human skulls (Vandenberghe et al. 2007). Mengel et al. found that CBCT offered better image quality than CT and Misch et al. concluded that CBCT offers a significant advantage over intraoral radiographs because all defects can be detected and quantified. Vandenberghe et al. stated that CBCT allowed similar periodontal bone level measurements as digital intraoral radiography but that craters and furcation involvements were better depicted by CBCT. Leung et al. (2010) studied accuracy and reliability of volume rendered CBCT images for measuring alveolar bone heights and for detecting bony dehiscences and fenestrations in dry skulls. They concluded that measurements in CBCT images, using a voxel size of 0.38mm, were less accurate than direct measurements on the skulls. Location of the CEJ was accurate to within 0.4mm, and location of the marginal bone crest to within 0.6mm. They concluded that alveolar bone height can be measured to an accuracy of about 0.6mm. Further, they found the diagnostic value of CBCT for the detection of buccal defects to be high for fenestrations but lower for dehiscences. Sun et al. (2011) investigated the effect of bone thickness and CBCT spatial resolution on alveolar bone height measurements in fresh porcine heads. They concluded that CBCT measurements of alveolar bone height could be made with good to excellent intra- and inter-rater repeatability for buccal and palatal/lingual surfaces. They remarked that, when the alveolar bone thickness was close to, or smaller, than the voxel size the distance between the cemento-enamel junction and the marginal bone crest could be overestimated. A decrease in voxel size from 0.4mm to 0.25mm improved measurement accuracy.

General aims

Some of the issues addressed in the report by the Swedish Council on Technology Assessment in Health Care concerning Malocclusions and Orthodontic Treatment in a Health Perspective can only be resolved by the use of a radiographic technique that is able to display root surfaces not visualized in conventional radiographs and that is insensitive to changes in tooth/root positions caused by the orthodontic treatment.

With the use of a CBCT unit yielding high quality images (Liang et al. 2010) at relatively low radiation doses to the patient the general aims of the present thesis, based on four studies later referred to by their roman numerals (I-IV), were to assess the frequency and severity of one well-known side effect of orthodontic treatment – root resorption – and to evaluate whether and to what degree another possible side effect – marginal bone level change – is associated with orthodontic treatment of a common type of malocclusion among adolescents.

Specific aims

The specific aims of the studies on which the present thesis are based were to:

- Assess accuracy and precision of linear measurements in images of a specifically constructed Plexiglas® model radiographed with a particular CBCT unit and to evaluate whether different object positions and reformatting systems have an influence on such measurements (*Study I*).

- Evaluate measurement accuracy *in vitro* with respect to root length and marginal bone level measurements in CBCT images of a human dry skull (*Study II).*

- Evaluate the *in vivo* precision of root length and marginal bone level measurements in CBCT images obtained during the course of orthodontic treatment (*Study II*).

- By means of CBCT determine the incidence and severity of root resorptions as a result of orthodontic treatment in a homogeneously treated group of adolescents and explore factors with a possible influence on the degree of root shortening (*Study III*).

- Evaluate the monthly rate of root resorption during the first six months of orthodontic treatment and during the time between a six-month control and the end of treatment (*Study III*).

- By means of CBCT determine the distance between the cemento-enamel junction and the marginal bone crest at proximal, buccal and palatal/lingual surfaces in adolescents about to undergo orthodontic treatment (*Study IV*).

- By means of CBCT investigate the incidence and degree of marginal bone level changes at proximal, buccal and palatal/lingual surfaces in adolescents after orthodontic treatment and relate it to factors with a possible influence on its severity (*Study IV*).

Material and methods

S*tudy I* and *Study II* are concerned with establishing the accuracy and precision of a radiographic method later to be used to assess root resorption and marginal bone level changes in a group of adolescents undergoing orthodontic treatment (*Study III-IV*). The latter studies are part of a comprehensive cooperative project between the Department of Orthodontics, Public Dental Service, Gothenburg, Sweden and the Department of Oral and Maxillofacial Radiology, Institute of Odontology, University of Gothenburg, Sweden. The human studies were approved by the Regional Ethical Review Board, Gothenburg, Sweden (626-05).

Study material (Study I-II)

The object used in *Study I* consisted of 12 Plexiglas® plates of varying thickness enclosed by thick Plexiglas blocks. In three of the plates, 2mm metal balls were incorporated forming a pattern with known distances between them (Figure 1).

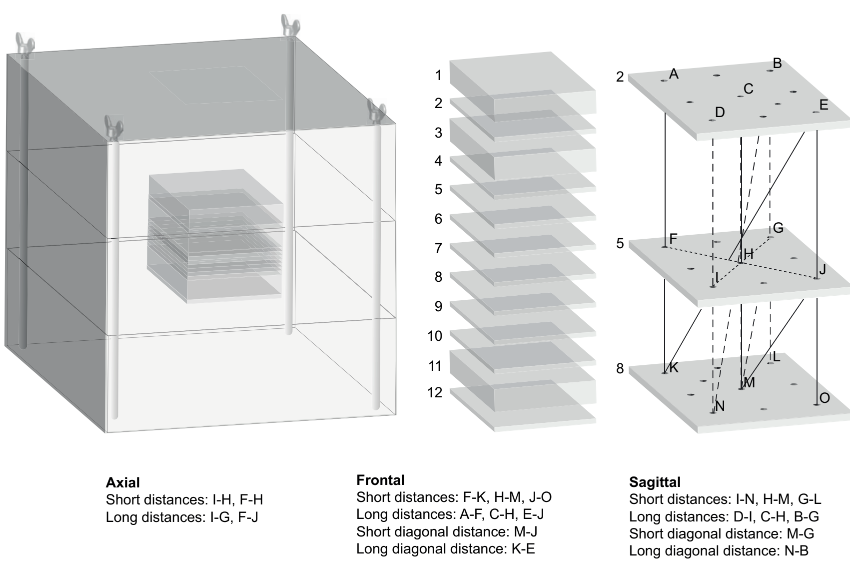


Figure 1. The measuring object in its enclosure, the position of the metal balls in 3 of 12 Plexiglas plates and the 20 linear distances measured.

The dry human skull used in *Study II* was well preserved. There were no signs of previous pathological processes in the jaws. The teeth were without restorations and the marginal alveolar bone showed no signs of periodontal bone loss.

For the *in vivo* assessments of intra-reader repeatability of measurements (*Study II*) a randomly selected sub-sample of patients described in *Study III-IV* was used.

Patients (Study III-IV)

From March 2005 to June 2008 consecutively incoming patients to the Department of Orthodontics, University Clinic of Odontology, Public Dental Service, Gothenburg, Sweden were invited to take part in the study. The following criteria had to be met: Age 9 to 18 years, good general health, Class I malocclusion (super Class I: cusp-to-cusp distal molar relationship) and an overjet ≤5 mm. The crowding had to be of an extent motivating the extraction of one premolar in each jaw quadrant. Figure 2 shows a typical patient before start of the orthodontic treatment. Informed consents from the patients' parents were obtained.

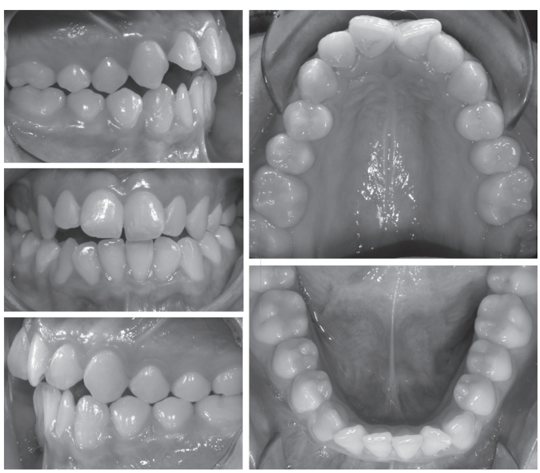


Figure 2. Intraoral photographs of a typical study participant. Courtesy of Associate Professor Ken Hansen.

Of 183 originally enrolled patients, 6.6% (5 boys, 7 girls, mean age 15.3 yrs) declined further participation, leaving 171 (75 boys, 96 girls, mean age 15.3 yrs) undergoing the first of 2 or 3 radiographic examinations. At the end of the study 152 patients (88% of the 171 patients) still remained (65 boys, 87 girls, mean age 17.4 yrs) as described in a flowchart in Figure 3. The age distribution of the patients at the start of the study is shown in Figure 4.

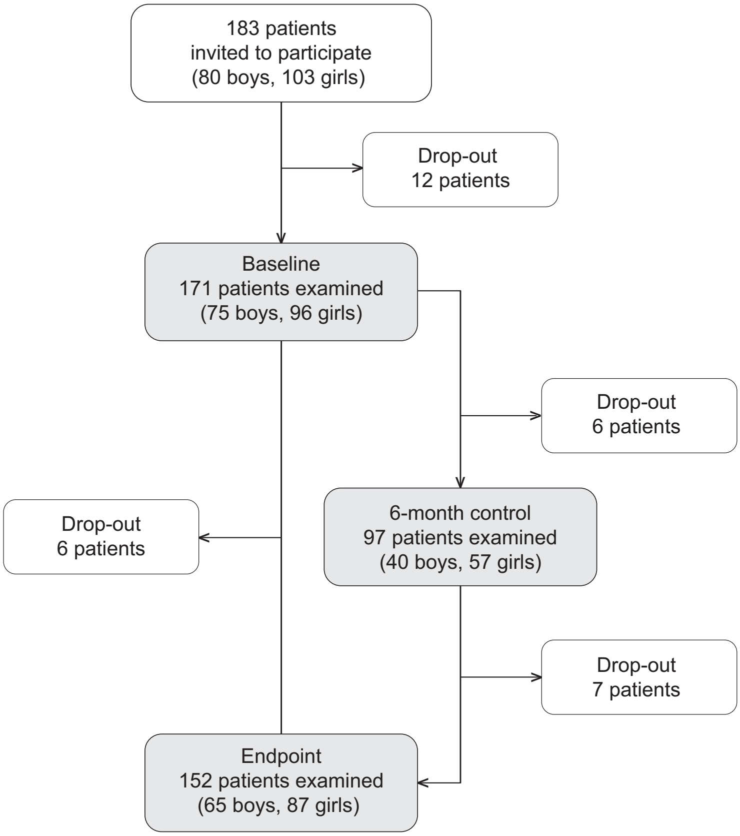


Figure 3. Flowchart describing the patient sample from invitation to Endpoint.

The participants received orthodontic treatment with fixed appliances. In accordance with the treatment plan, 582 (48%) premolars were extracted. In five patients no extractions were made and in four patients two or three premolars were removed. The treatment protocol was standardized using a MBT pre-adjusted appliance (3M Unitek Orthodontic Products, Monrovia, Calif, U.S.A.) with .022-inch slots. Initial leveling and alignment were done using round, heat activated, nickel titanium wires and space closures were performed using rectangular .019 x .025 stainless steel wires. Class I elastics were mainly used and, sometimes, additional Class II elastics. Mean treatment time was 20.7 months (median 20.0, SD 5.7, range 11-43), during which the oral hygiene was continuously monitored.

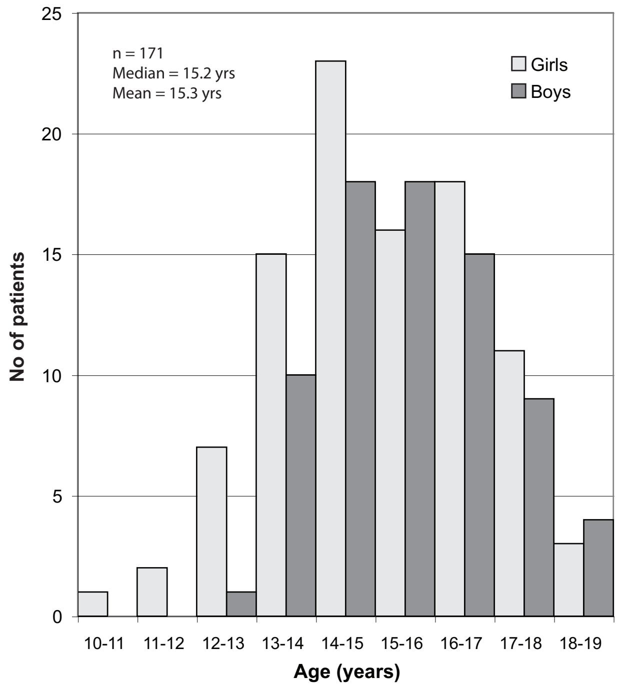


Figure 4. Age distribution by gender among study participants at Baseline.

Radiographic equipment and workstations

In all studies cone beam computed tomography (CBCT) was performed with a 3DX Accuitomo FPD unit (J. Morita Mfg. Corp., Kyoto, Japan) (Figure 5). The unit is equipped with a flat panel detector working with a 12-bit gray scale depth and an isotropic voxel size of 0.125mm. The equipment permits a choice of two fields-of-view: 40mm x 40mm and 60mm x 60mm. The x-ray tube tension can be set to 60-80 kilovolts (kV) in 1kV increments and the tube current to 1-10 milliamperes (mA) in increments of 0.1mA.

Figure 5. Patient positioned for examination in the CBCT unit.

The exposure is continuous and the exposure time is 17.5s for a 360° rotation during which raw data from approximately 556 projections are recorded. To ensure a correct position of the x-ray tube and detector and, thus, of the image volume laser light lines are, as a rule, used even though scout images can be used for the same purpose.

After each exposure a primary reconstruction of data is made by the acquisition software (i-Dixel-3DX, 3D, Version 1.691; J. Morita Mfg. Corp., Kyoto, Japan) at the CBCT workstation, resulting in perpendicular views in axial, coronal and sagittal planes. Secondary reconstructions can be made either at the CBCT workstation, with the ability to choose a slice thickness and interval of 0.125-2mm, or by sending image slices to PACS (Picture Archiving and Communication System) via DICOM-export and utilize this system's inherent MPR (Multi-Planar Reconstruction) function.

The workstation at the CBCT unit consists of a Dell computer with a 32-bit graphic card and a 19-inch flat panel TFT color monitor (1280x1024) and utilizes i-Dixel software. The PACS workstation comprises a Dell computer with a 32-bit graphic card and three 20-inch flat panel monitors, one color and two monochromatic (1600x1200) and utilizes Sectra PACS, IDS5™ software (Sectra Imtec AB, Linköping, Sweden).

Radiographic examinations

The Plexiglas object (*Study I*) was placed on a horizontal platform firmly attached to the chair of the CBCT unit. A first examination was made with the object in a central position between the x-ray tube and the detector and with the light line indicators centered in the middle of the object (Basic position). A second examination was made with the object placed in a position 10mm closer to the x-ray tube (Deviated position) and a third one was made with the object tilted 20° anteriorly (Rotated position). Exposure parameters were 75kV and 10mA (360° rotation).

The human skull (*Study II)* was placed in a Plexiglas bowl filled with water to obtain x-ray attenuation and scatter radiation as from soft tissues. Positioning of the light lines and, thus, of the image volume (60mm x 60mm) was made as for the patient examinations, that is, so that the image volume would encompass all teeth from incisors to first molars in both jaws. For the skull examination exposure parameters were 75kV and 5mA.

In the patient examinations (*Study III-IV*) an FOV of 60mm x 60 mm was used. Exposure parameters were 75kV, the mA varied between 4.5-5.5 – depending on subject size – and a 360° rotation was employed. Using similar exposure parameters and the same FOV, investigators (Hirsch et al. 2008, Okano et al. 2009, Suomalainen et al. 2009) have calculated effective doses in the range 0.043-0.166mSv (ICRP 103) depending on, e.g. the region being exposed.

Data processing

Secondary reconstructions were made at the CBCT workstation and at the Sectra PACS workstation from axial slices that had been exported from the CBCT workstation using DICOM-export. The secondary reconstructions of the images of the Plexiglas object were made to obtain optimal visibility of the metal balls in axial, coronal and sagittal planes, and in two diagonal planes achieved by a 45° horizontal rotation of the image stack.

For the assessment of root lengths and marginal bone levels in images of the skull phantom, as well as of patients, reconstructions were made so that the axial slices became perpendicular to the long axis of the tooth/root. This provided optimal visualization of the tooth/root and the marginal bone crest (MBC) in relation to the cemento-enamel junction (CEJ) in axial, coronal, and sagittal planes.

Measurement procedures

In the Plexiglas object (*Study I*), two observers independently measured 20 linear distances (Figure 1) between the metal balls both at the CBCT workstation and at the Sectra PACS workstation. Measurements were made between the centers of the balls using the workstations' inherent measurement functions. They were repeated after approximately 6 months. When all measurements were made, the enclosing was opened and the distances between the metal balls were measured five times using a digital caliper. The mean of the five measurements for each distance was then calculated and used as a "gold standard" for comparison with measurements made in the radiographs.

In the human skull (*Study II*) five teeth, representing all tooth groups, were chosen from the upper right and lower left jaw quadrant, respectively. In the sub-sample of patients (*Study II*) two teeth per subject and tooth group and one root from multi-rooted teeth were randomly chosen. For the root length measurements a reference line was placed that connected the buccal and palatal/lingual CEJs and, parallel to this, a line was positioned at the root apex (Figure 6). For marginal bone level measurements a reference line was placed, either between the CEJs at the buccal and palatal/lingual surface or between the CEJs at the mesial and distal surface, depending on what marginal bone crest to evaluate. Parallel to the respective reference line a new line was placed at the MBC at the buccal, lingual, mesial and distal surface, respectively (Figure 7). In the skull material the perpendicular distance between reference line and bone crest was measured five times. In the sub-sample of patients it was

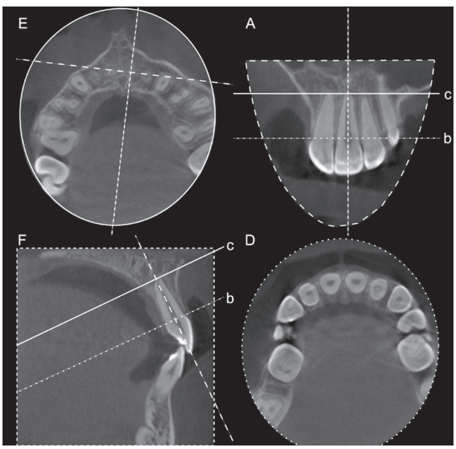


Figure 6. Measurement procedure for assessment of root length by means of axial, coronal and sagittal slices. Measurements were made in the coronal view (A) between two reference lines, one at the cemento-enamel junction (b) and one at the root apex (c). Corresponding axial views (D,E) and sagittal view (F) were used to ensure proper positioning of reference lines.

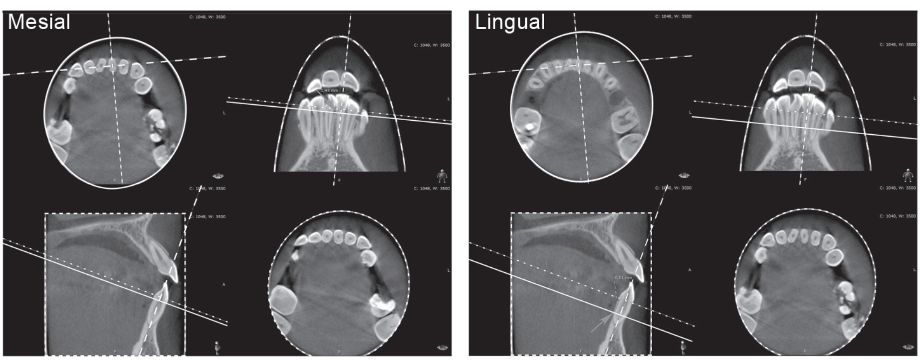


Figure 7. Assessment of marginal bone level at tooth 31, exemplified for its mesial and lingual surface, by means of reformatted images in axial, sagittal and coronal planes. Measurements were made between two reference lines, one at cemento-enamel junction (CEJ) and the other at the marginal bone crest (MBC).

measured twice for each tooth/surface and examination (Baseline, 6-Month and Endpoint).

When all measurements had been made in the skull radiographs, the marginal bone crest around the teeth was marked onto the root surface with a thin pencil. Thereafter, the teeth were gently removed from their sockets. With a digital caliper root lengths were measured from the apices to the CEJs while the marginal bone levels were measured from the CEJs to the aforementioned markings, representing the MBCs, on the root surfaces.

In the patient radiographs (*Study III-IV*) measurements were made once for each examination (Baseline, 6-Month and Endpoint) at fully erupted teeth where the CEJ and MBC could be clearly identified. For the evaluation of root length, data from all examinations were used, whilst evaluation of marginal bone levels utilized only Baseline and Endpoint examinations. 6-Month and Endpoint measurements were made without access to previous radiographs or protocols. Surface resorptions (slanted resorptions), not resulting in root shortening, were registered at buccal, palatal/lingual and proximal surfaces (Figure 8) as were teeth with incomplete root development.

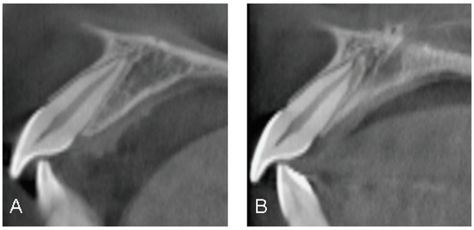


Figure 8. Example of a maxillary central incisor at Baseline (A) with palatal surface resorption at Endpoint (B).

With the exception of the distal root of the lower first molar that was unreadable in 32%, because it was not always contained in the imaged volume, few roots were unreadable as can be derived from Table 5b.

As regards marginal bone level assessments 0.7% of the surfaces could not be evaluated at Baseline due to the presence of partially erupted teeth, absence of surfaces because they were not contained in the image volume, or difficulties in identifying the CEJ and/or the MBC. Among tooth groups the number of unreadable surfaces varied between 0-3% with mandibular molars and maxillary canines showing the highest percentages: 3% and 2.3%, respectively. At Endpoint, an average of 1.4% could not be evaluated (0.1-4.2%) with the maxillary canines and mandibular molars showing the highest percentages: 3.5% and 4.2%, respectively (Table 3).

Table 3. Number of teeth, surfaces and unreadable bone surfaces among tooth groups at Baseline and/or Endpoint

Tooth group	16/26	15/14 25/24	13/23	12/22	11/21	41/31	42/32	43/33	45/44 34/35	46/36	Total (n)
No of teeth	304	314	304	304	304	304	304	304	320	304	3066
No of surfaces	1216	1256	1216	1216	1216	1216	1216	1216	1280	1216	12264
No of unreadable surfaces											
buccal	18	4	15	2	5	1	1	5	5	18	74
palatal/lingual	0	2	9	0	0	1	0	1	4	6	23
mesial	0	2	9	1	2	0	0	1	4	6	25
distal	6	2	9	0	0	0	0	1	4	21	43
Total n (%)	24 (2.0)	10 (0.8)	42 (3.5)	3 (0.3)	7 (0.6)	2 (0.2)	1 (0.1)	8 (0.7)	17 (1.3)	51 (4.2)	165 (1.4)

Statistical analyses

Study I

Bland-Altman plots (Bland & Altman 2003) were used to describe differences between the "gold standard" and the radiographic measurement values (mean of two observers) obtained from i-Dixel and Sectra MPR reconstructions and the influence of different object positions. Linear regression analyses were used to investigate whether there were differences between measurements due to reconstruction planes and Wilcoxon signed rank test to analyze differences due to object positioning. A p-value $<.05$ was used as cut-off value for statistical significance.

Study II

Descriptive statistics was used for the *in vitro* comparison between direct physical and radiographic measurements of root lengths and marginal bone levels. Student's paired t-test was used for significance testing. The precision of the *in vivo* assessments of root lengths and bone levels at Baseline, 6-Month control and Endpoint was calculated using the formula $s=\sqrt{\sum d^2/2n}$ (Dahlberg 1940), where d=difference between duplicate determinations and n=number of determinations. To evaluate any differences between the three occasions Student's paired t-test was used. Differences were considered statistically significant at $p<.05$.

Study III

Changes in root length between Baseline and subsequent examinations are presented by means of descriptive statistics. Root shortening was evaluated with a mixed covariance pattern model including a compound symmetry covariance model to estimate the dependence within patients. Analysis of changes in root length per month during the two observation periods were made with Wilcoxon signed rank test using a significance level of $p<.05$.

Study IV

Marginal bone levels at Baseline were analyzed by means of descriptive statistics (cumulative percentages of CEJ-MBC distances, means, medians, and SDs). Differences between genders were analyzed by means of Mann-Whitney U-test and the influence of age by means of Pearson's correlation coefficient.

Differences in bone level changes between maxillary and mandibular teeth from Baseline to Endpoint were analyzed by means of Wilcoxon signed rank test. Differences between genders were analyzed using Wilcoxon two-sample test. For correlation between age and treatment time, respectively, and bone level changes at buccal and palatal/lingual surfaces Spearman's correlation coefficient was used. All significance tests were two-tailed and made on patient basis with $p<.05$ indicating significant differences.

Results

Measurement accuracy and precision (Study I-II)

The differences between "gold standard" measurements and measurements made in images of the Plexiglas object, placed in different positions, are shown as Bland-Altman plots in Figure 9. The mean differences when using the Accuitomo workstation were below -0.09mm and when using the Sectra PACS workstation they were below -0.13mm.

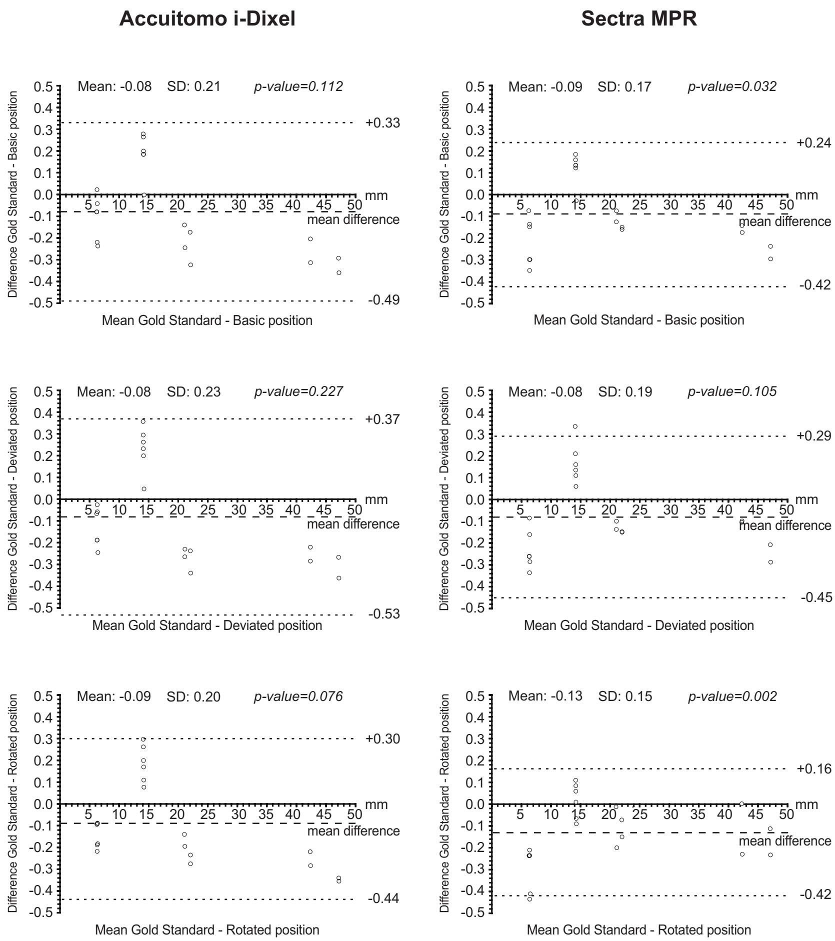


Figure 9. Bland-Altman plots for each workstation and object positioning.

Mean differences between direct physical measurements on the dry skull and corresponding radiographic measurements were 0.05mm (SD 0.75) for root lengths and -0.04mm (SD 0.54) for marginal bone level assessments.

The precision of the measurements made in radiographs of patients (*Study II*) at Baseline, 6-Month control and Endpoint (n=13) is shown in Figure 10. The error for root length measurements was at most 0.32mm and for bone level measurements at Baseline and Endpoint 0.31mm. There were no statistically significant differences between measurement errors in radiographs from the three examinations (p<.05).

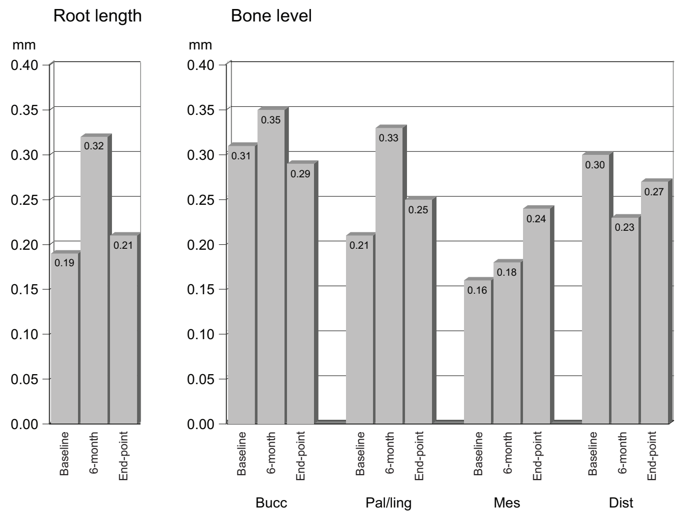


Figure 10. Precision of radiographic *in vivo* assessments of root length and marginal bone levels at Baseline, 6-Month and Endpoint examinations.

Root shortening – Baseline to 6-Month to Endpoint (Study III)

In Table 4 root lengths at Baseline are shown together with the number of teeth with incomplete root development. The latter did not amount to more than 1.6% (n=61) of all teeth.

Table 4. Root lengths and number of teeth with incomplete root development at Baseline

	n	Open apex	Mean	Median	SD	Min	Max
Upper jaw							
Central incisor	304		13.6	13.8	1.6	9.4	17.1
Lateral incisor	304	1	13.7	13.9	1.7	8.2	19.3
Canine	296	7	17.0	17.2	2.1	11.4	22.1
Premolar							
single-rooted	234	14	13.7	13.9	2.1	7.8	18.0
buccal	78	5	13.6	13.6	1.5	10.5	17.0
palatal	78	5	13.0	13.2	2.1	12.0	16.4
First molar							
mesiobuccal	295	1	13.4	13.5	1.4	10.0	17.0
distobuccal	292		13.2	13.2	1.4	9.8	17.2
palatal	302		14.6	14.5	1.5	10.8	20.4
Lower jaw							
Central incisor	304		13.1	13.2	1.3	9.2	16.9
Lateral incisor	304		14.5	14.6	1.3	10.6	18.1
Canine	296	8	16.2	16.4	1.7	10.8	20.3
Premolar	314	20	14.9	15.0	1.7	10.2	19.3
First molar							
mesial	282		14.7	14.7	1.4	10.5	17.8
distal	208		14.0	14.1	1.3	10.3	17.3

At the 6-Month control the highest frequencies of root shortening of more than 1mm were found at both roots of two-rooted maxillary premolars (30%), at maxillary and mandibular lateral incisors, and at maxillary single-rooted premolars (16%-17%) (Table 5a). The monthly rate of root shortening of the maxillary teeth during the two periods was higher after the 6-Month control than before for all teeth with the exception of the mandibular lateral incisor.

Table 5a Number and percentages (in italics) of roots with different extent of root shortening from Baseline to 6-Month control

	n	>0mm		>1mm		>2mm		>3mm		>4mm
Upper jaw										
Central incisor	194	145	*(74.7)*	26	*(13.4)*	4	*(2.1)*			
Lateral incisor	194	133	*(68.6)*	32	*(16.5)*	3	*(1.5)*			
Canine	189	122	*(64.6)*	21	*(11.1)*	2	*(1.1)*			
Premolar										
single-rooted	156	94	*(60.3)*	25	*(16.0)*	1	*(0.6)*	1	*(0.6)*	
buccal	44	29	*(65.9)*	13	*(29.5)*	2	*(4.5)*			
palatal	44	34	*(77.3)*	13	*(29.5)*	2	*(4.5)*			
First molar										
mesiobuccal	190	99	*(52.1)*	10	*(5.3)*					
distobuccal	184	110	*(59.8)*	18	*(9.8)*	2	*(1.1)*			
palatal	192	117	*(60.9)*	16	*(8.3)*	2	*(1.0)*	1	*(0.5)*	
Lower jaw										
Central incisor	194	109	*(56.2)*	21	*(10.8)*	1	*(0.5)*			
Lateral incisor	194	144	*(74.2)*	31	*(16.0)*	2	*(1.0)*			
Canine	188	120	*(63.8)*	18	*(9.6)*	3	*(1.6)*			
Premolar	200	115	*(57.5)*	14	*(7.0)*					
First molar										
mesial	182	102	*(56.0)*	12	*(6.6)*					
distal	121	63	*(52.1)*	10	*(8.3)*					

The difference was statistically significant only with respect to the maxillary lateral incisor. Radiographs from all three examinations of a patient with severe root shortening of the incisors are shown in Figure 11.

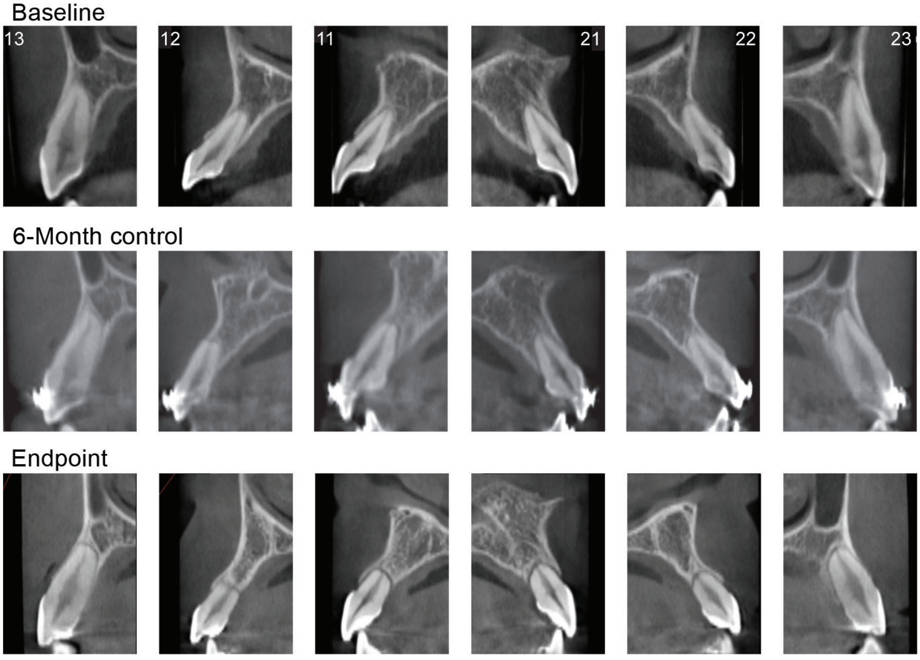


Figure 11. A case with severe root shortening during the course of treatment. Teeth numbered according to FDI.

In 94% of the patients root shortenings of ≥1mm was found in one or more teeth (Figure 12). Approximately 1% of the patients had 14 teeth with root shortenings ≥1mm. About 50% of the patients had root shortenings of ≥2mm in one or more teeth, 23% of them had root shortenings ≥3mm, and around 7% of the patients had root shortenings that were ≥4mm in one or more teeth. None had more than 4 teeth with root shortenings ≥4mm.

The maxillary lateral incisors showed the highest frequencies of shortened roots. In 56% of them a root shortening of more than 1mm was found (Table 5b). In 8% the root resorption was >3mm and in 3% it exceeded 4mm. Thus, the maxillary lateral incisor was one of the teeth with the most extensive root shortening. High frequencies of root resorptions of similar extents were also found at e.g. the maxillary central incisors, the palatal root of the maxillary premolar and the mandibular lateral incisors. The extent of root resorptions was significantly larger (p<.05) in maxillary than in mandibular teeth and in front teeth compared with posterior ones. Gender, root length at Baseline, and treatment duration were not significantly associated with the extent of root shortening.

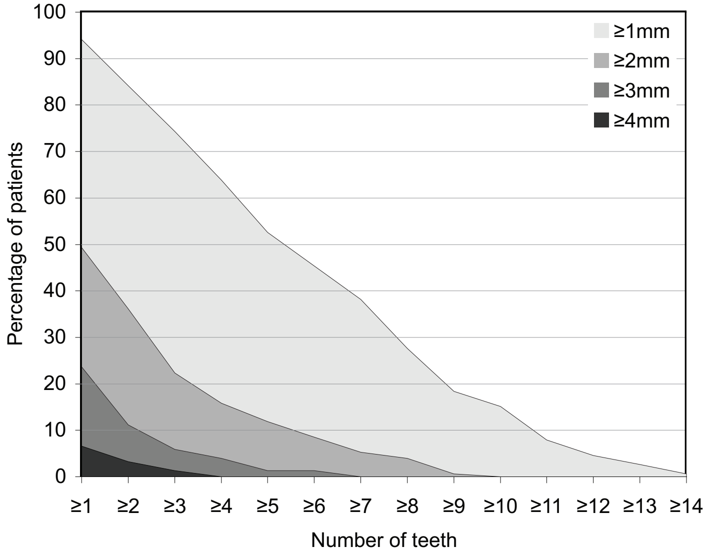


Figure 12. Percentage of patients with root shortening by extent and number of affected teeth.

Table 5b. Number and percentages (in italics) of roots with different extent of root shortening from Baseline to Endpoint

	n	>0mm		>1mm		>2mm		>3mm		>4mm	
Upper jaw											
Central incisor	304	266	*(87.5)*	126	*(41.4)*	44	*(14.5)*	21	*(6.9)*	8	*(2.6)*
Lateral incisor	304	278	*(91.4)*	171	*(56.3)*	67	*(22.0)*	25	*(8.2)*	8	*(2.6)*
Canine	296	208	*(70.3)*	79	*(26.7)*	19	*(6.4)*	4	*(1.4)*	1	*(0.3)*
Premolar											
single-rooted	235	153	*(65.1)*	49	*(20.9)*	6	*(2.6)*	1	*(0.4)*		
buccal	78	53	*(67.9)*	21	*(26.9)*	6	*(7.7)*	4	*(5.1)*	1	*(1.3)*
palatal	78	45	*(57.7)*	30	*(38.5)*	11	*(14.1)*	5	*(6.4)*	2	*(2.6)*
First molar											
mesiobuccal	295	172	*(58.3)*	22	*(7.5)*	1	*(0.3)*				
distobuccal	292	208	*(71.2)*	55	*(18.8)*	8	*(2.7)*	2	*(0.7)*		
palatal	302	200	*(66.2)*	61	*(20.2)*	6	*(2.0)*	2	*(0.7)*		
Lower jaw											
Central incisor	304	235	*(77.3)*	76	*(25.0)*	13	*(4.3)*	1	*(0.3)*		
Lateral incisor	304	260	*(85.5)*	131	*(43.1)*	36	*(11.8)*	7	*(2.3)*		
Canine	296	208	*(70.3)*	80	*(27.0)*	27	*(9.1)*	9	*(3.0)*		
Premolar	314	172	*(54.8)*	44	*(14.0)*	9	*(2.9)*				
First molar											
mesial	282	185	*(65.6)*	39	*(13.8)*	5	*(1.8)*	1	*(0.4)*		
distal	208	136	*(65.4)*	56	*(26.9)*	11	*(5.3)*	4	*(1.9)*	1	*(0.5)*

Slanted surface resorptions (Figure 8) occurred most frequently at palatal surfaces of maxillary central and lateral incisors. They were found in 15% of the former surfaces and 12% of the latter (Table 6).

Table 6. Percentage of slanted surface resorption per surface

	n	Buccal	Palatal/ Lingual	Proximal
Upper jaw				
Central incisor	304	6.9	15.1	6.6
Lateral incisor	304	2.0	11.5	9.9
Canine	296	1.0	4.1	3.7
Lower jaw				
Central incisor	304	1.3	4.9	0.0
Lateral incisor	304	1.6	2.3	0.7
Canine	296	1.4	2.4	4.4

Among patients, 57% had this type of resorption at ≥1 tooth and 11% had it at ≥4 teeth, regardless of affected surface (Figure 13).

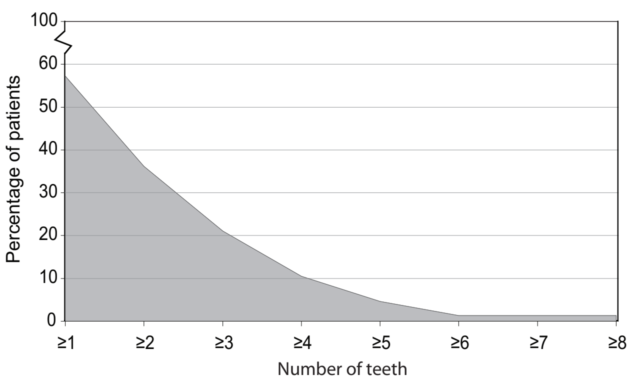


Figure 13. Percentage of patients with slanted surface resorption (resorption not having resulted in root shortening) by number of affected teeth.

Marginal bone level – Baseline (Study IV)

Distances between CEJ and MBC for all tooth groups and tooth surfaces are shown in Figures 14a and b. The graphs demonstrate large differences among teeth and, in particular, tooth surfaces. For example, 85% of the buccal surfaces of maxillary canines have a CEJ-MBC distance of >2mm and 21% of >4mm with the largest distance being 13.6mm. In the mandible 68% of the central incisors had a CEJ-MBC distance of >2mm and 19% a distance of >4mm.

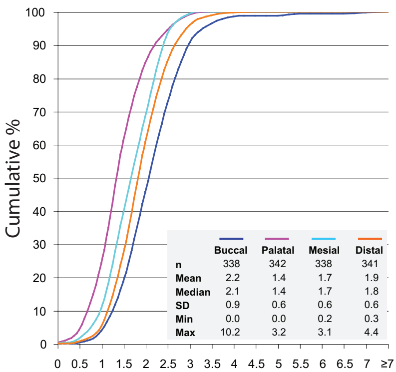
With regard to proximal surfaces at incisors, 20% to 56% exhibit a CEJ-MBC distance >2mm. A distance >3mm is found in 1% to 9% with the largest value for the distal surface of the maxillary lateral incisor. A distance of >4mm is found in 3% of these surfaces. Among canines, the percentage of proximal surfaces with a CEJ-MBC distance >2mm range between 8% and 22%. Less than 1% of the proximal surfaces of the canines exhibit a distance >3mm.

Among proximal surfaces in premolars and molars a CEJ-MBC distance >2mm is found in between 2% (mesial surface of mandibular first molar) and 16% (distal surface of maxillary first molar). With the exception of the distal surface of the maxillary first molar (3%), less than 1% of the posterior proximal surfaces show a distance >3mm.

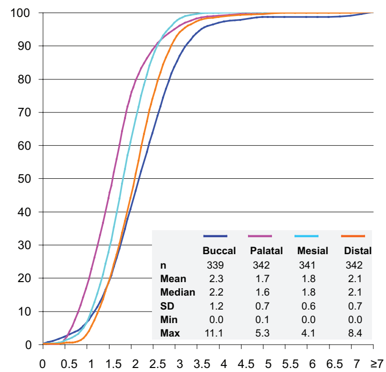
No statistically significant differences were found between genders either for buccal and palatal/lingual surfaces at front teeth or when including all teeth. Slight, but statistically significant correlations between age and the CEJ-MBC distance were found. Only 3% to 7% of the variation in the CEJ-MBC distances could be explained by the variation in age.

Maxilla

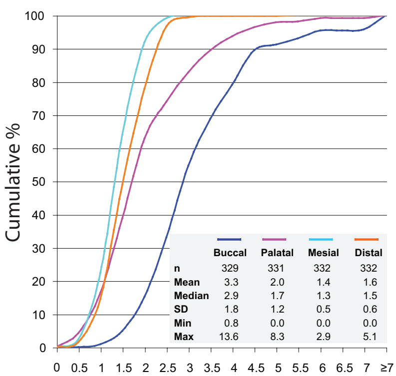
Central incisors



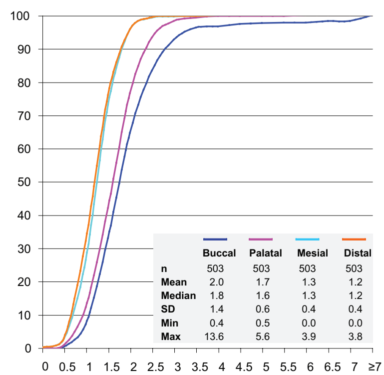
Lateral incisors



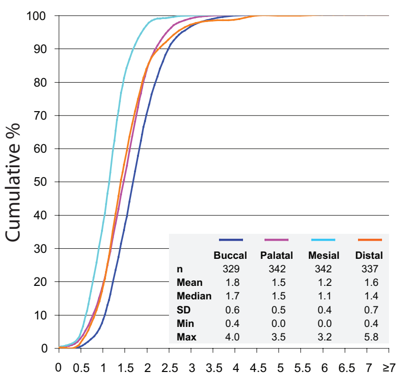
Canines



Premolars

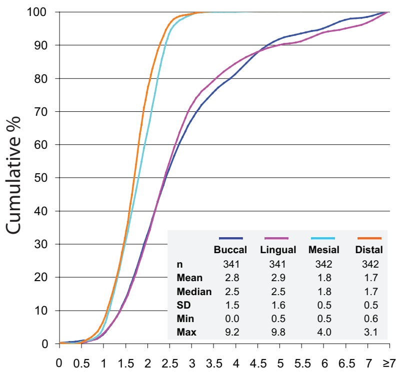


First molars

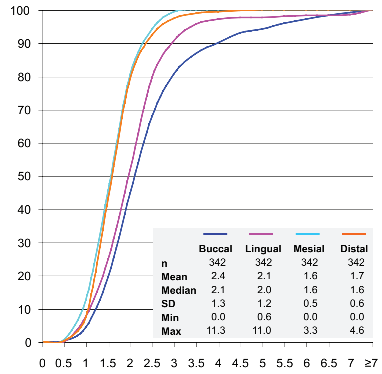


Mandible

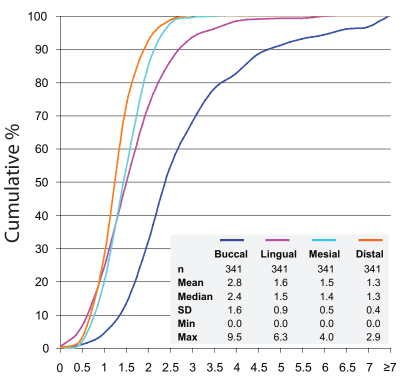
Central incisors



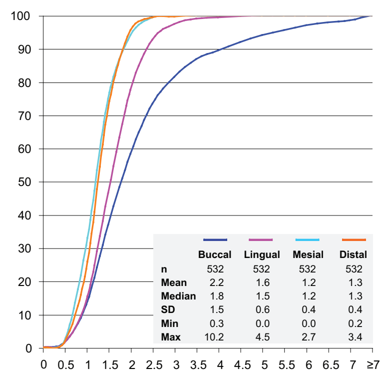
Lateral incisors



Canines



Premolars



First molars

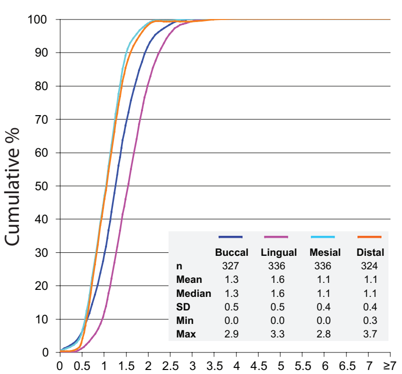


Figure 14. Cumulative percentages of CEJ-MBC distances (mm) at different tooth groups and surfaces at Baseline.

Marginal bone level changes– Baseline to Endpoint (Study IV)

Changes in CEJ-MBC distances between Baseline and Endpoint range between a mean decrease of 0.2mm (distal surface of maxillary central incisor) to an average increase of 5.7mm (lingual surface of mandibular central incisor). Palatal/lingual surfaces, followed by buccal surfaces, show the largest changes. The changes vary widely between tooth groups (Table 7).

Table 7. Number and percentages (in italics) of surfaces with different increase (mm) of CEJ-MBC distances between Baseline to Endpoint. Negative mean values indicate a decreased CEJ-MBC distance

Maxilla	n	Mean	SD	>0mm	>2mm	>4mm	>6mm	>8mm
Central incisors								
Buccal	299	0.2	0.9	186 *(62.2)*	2 *(0.7)*	1 *(0.3)*		
Palatal	304	1.0	1.5	237 *(78.0)*	48 *(15.8)*	17 *(5.6)*	5 *(1.6)*	
Mesial	302	0.1	0.6	168 *(55.6)*				
Distal	304	-0.2	0.6	112 *(36.8)*				
Lateral incisors								
Buccal	302	0.6	1.5	226 *(74.8)*	18 *(6.0)*	7 *(2.3)*	5 *(1.7)*	2 *(0.7)*
Palatal	304	1.3	2.1	237 *(78.0)*	65 *(21.4)*	31 *(10.2)*	19 *(6.3)*	4 *(1.3)*
Mesial	303	0.0	0.7	153 *(50.5)*				
Distal	304	0.0	0.8	151 *(49.7)*	2 *(0.7)*			
Canine								
Buccal	289	0.1	1.8	169 *(58.5)*	18 *(6.2)*	6 *(2.1)*	2 *(0.7)*	1 *(0.3)*
Palatal	295	0.6	1.5	217 *(73.6)*	48 *(16.3)*	7 *(2.4)*		
Mesial	295	0.0	0.6	152 *(51.5)*				
Distal	295	0.1	0.6	178 *(60.3)*				
Premolars								
Buccal	310	0.2	1.6	204 *(65.8)*	2 *(0.6)*	1 *(0.3)*	1 *(0.3)*	1 *(0.3)*
Palatal	312	0.3	0.8	218 *(69.9)*	8 *(2.6)*			
Mesial	312	0.1	0.6	181 *(58.0)*	2 *(0.6)*			
Distal	312	0.1	0.5	180 *(57.7)*	1 *(0.3)*			
Molar								
Buccal	286	0.2	0.8	183 *(64.0)*	3 *(1.0)*	2 *(0.7)*	2 *(0.7)*	
Palatal	304	0.3	0.6	192 *(63.2)*	1 *(0.3)*			
Mesial	304	0.2	0.6	187 *(61.5)*	1 *(0.3)*			
Distal	298	0.0	0.7	149 *(50.0)*				

Mandible	n	Mean	SD	>0mm	>2mm	>4mm	>6mm	>8mm
Central incisors								
Buccal	303	0.8	1.9	205 *(67.7)*	67 *(22.1)*	18 *(5.9)*	2 *(0,7)*	
Lingual	303	5.7	3.3	289 *(95.4)*	253 *(83.5)*	220 *(72.6)*	160 *(52,8)*	82 *(27,1)*
Mesial	304	0.1	0.6	177 *(58.2)*	2 *(0.7)*			
Distal	304	0.1	0.5	164 *(53.9)*				
Lateral incisors								
Buccal	303	1.1	2.0	226 *(74.6)*	73 *(24.1)*	27 *(8.9)*	7 *(2,3)*	
Lingual	304	5.1	3.9	277 *(91.1)*	201 *(66.1)*	172 *(56.6)*	143 *(47,0)*	91 *(29,9)*
Mesial	304	-0.1	0.6	106 *(34.9)*				
Distal	304	-0.1	0.6	137 *(45.1)*				
Canine								
Buccal	299	1.2	2.5	221 *(73.9)*	82 *(27.4)*	41 *(13.7)*	19 *(6,4)*	5 *(1,7)*
Lingual	303	1.4	1.9	245 *(80.9)*	77 *(25.4)*	22 *(7.3)*	11 *(3,6)*	4 *(1,3)*
Mesial	303	0.0	0.6	146 *(48.2)*				
Distal	303	0.1	0.6	161 *(53.1)*				
Premolars								
Buccal	315	0.6	1.6	228 *(72.4)*	44 *(14.0)*	12 *(3.8)*	3 *(1,0)*	
Lingual	316	0.6	0.9	251 *(79.4)*	19 *(6.0)*	2 *(0.6)*	1 *(0,3)*	
Mesial	316	0.2	0.6	189 *(59.8)*	1 *(0.3)*			
Distal	316	0.1	0.5	175 *(55.4)*				
Molar								
Buccal	286	0.3	0.9	181 *(63.3)*	5 *(1.7)*	3 *(1.0)*	3 *(1,0)*	
Lingual	298	0.2	0.6	183 *(61.4)*	1 *(0.3)*			
Mesial	298	0.1	0.5	174 *(58.4)*				
Distal	283	0.1	0.5	162 *(57.2)*				

Of the lingual surfaces at the mandibular central incisors 84% exhibit an increased CEJ-MBC distance of >2mm, 73% >4mm, 53% >6mm and 27% an increase exceeding 8mm. The lingual surface of the lower lateral incisor in 30% shows a change >8mm in the CEJ-MBC distance. In contrast, smaller changes are found at molars. All changes at buccal and palatal/lingual surfaces, except for the buccal surface of maxillary canines are statistically significant. Figure 15 shows sagittal images of mandibular front teeth from a patient showing a large increase of the CEJ-MBC distance at the lower incisors between Baseline and Endpoint. Few proximal surfaces exhibit an increase in the CEJ-MBC distance >2mm.

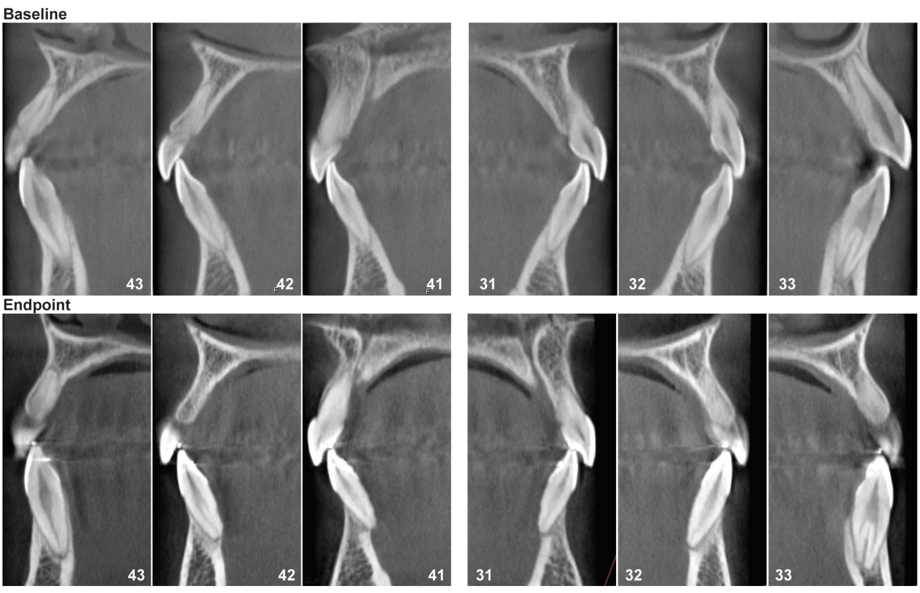


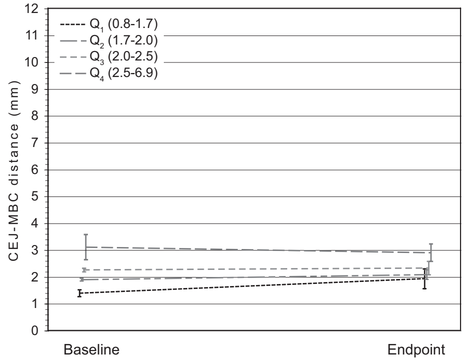
Figure 15. Sagittal images of mandibular frontal teeth (43-33) from a patient showing a large increase of the CEJ-MBC distance between Baseline and Endpoint. Teeth numbered according to FDI.

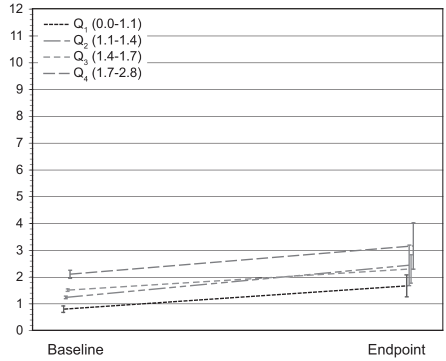
The Baseline CEJ-MBC distances for buccal and palatal/lingual surfaces of the front teeth were divided into quartiles (Q_1-Q_4). These values and the corresponding ones at Endpoint are found in Figures 16a and b. All surfaces belonging to Q_1 at Baseline, and most belonging to Q_2 and Q_3, show larger mean distances at Endpoint. For those belonging to Q_4 five (all lingual surfaces except that at maxillary canine) out of twelve surfaces show larger CEJ-MBC distances at Endpoint. For the remaining seven surfaces it either remains stable (n=2) or shows a slight decrease (n=5).

Maxilla

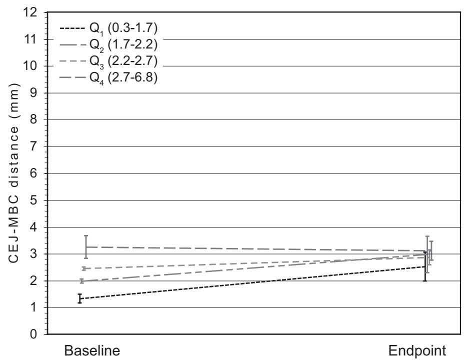
Buccal | Palatal

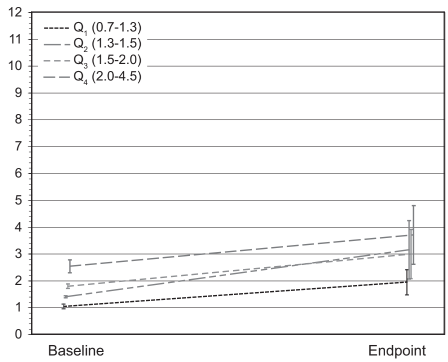
Central incisors



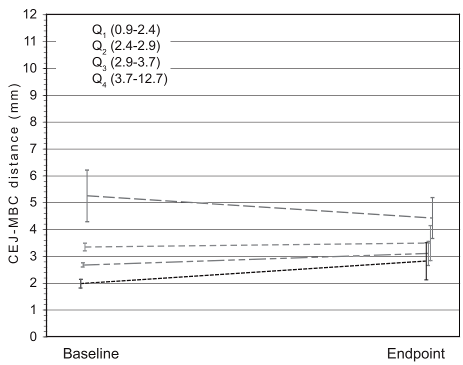


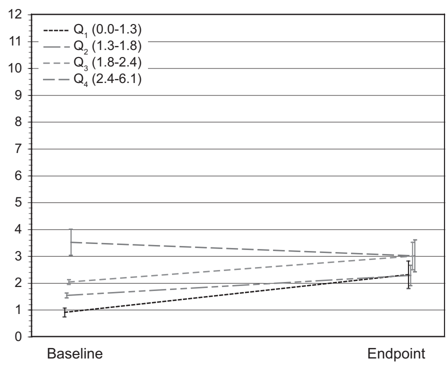
Lateral incisors





Canines





Mandible

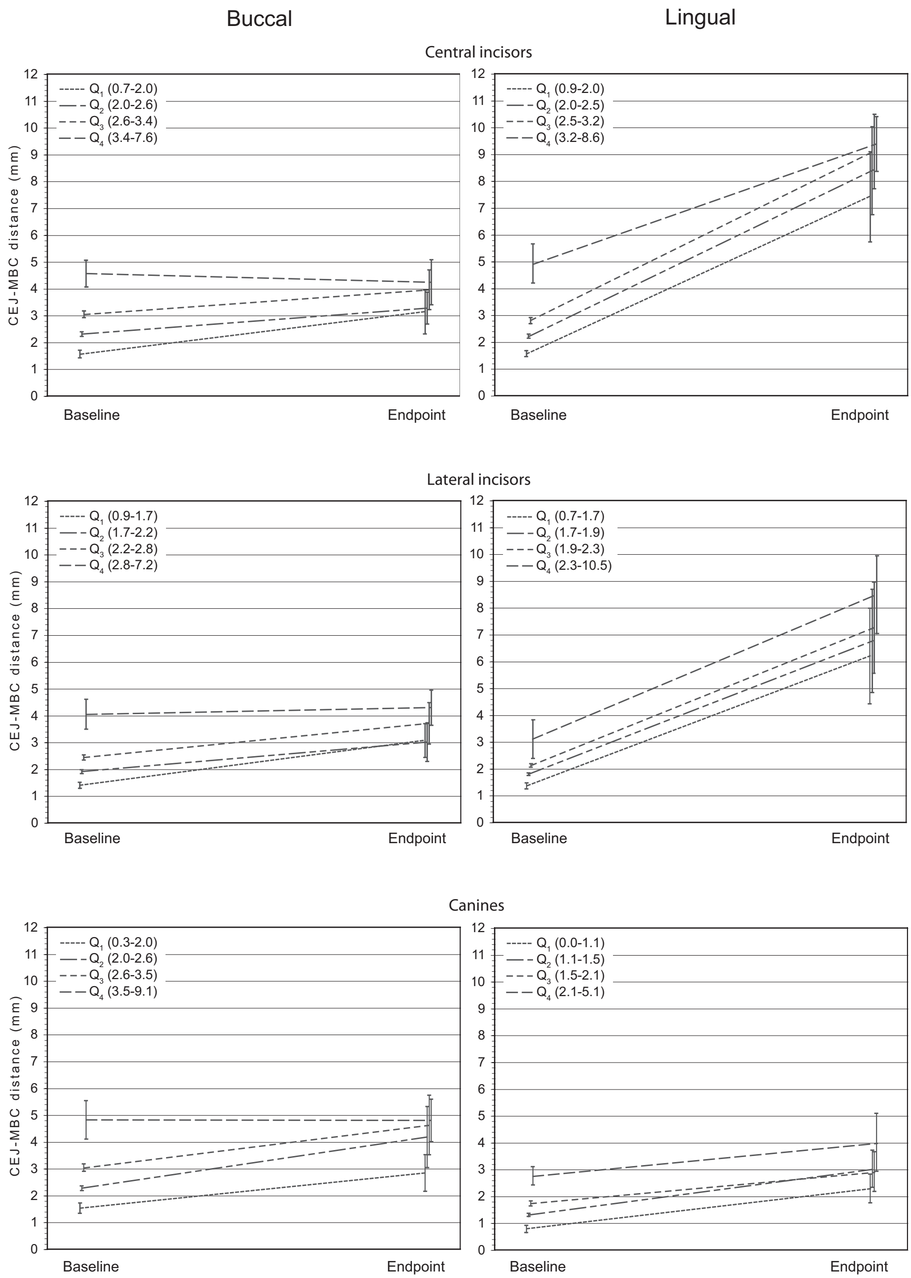


Figure 16. The CEJ-MBC distances at Baseline, divided in quartiles (Q_1-Q_4), and their values at Endpoint for buccal and palatal/lingual surfaces at front teeth.

When including all teeth in the analysis a significantly larger increase of the CEJ-MBC distance is found at palatal/lingual surfaces among girls (mean 1.8mm, SD 0.90) than among boys (mean 1.5mm, SD 0.77). For buccal surfaces no such difference is found. Neither for buccal, nor for palatal/lingual surfaces, a significant correlation between age at Baseline, or treatment time, and changes in the CEJ-MBC distance can be found. A statistically significant difference is found between the maxilla and the mandible with respect to buccal and lingual surfaces. The largest changes in CEJ-MBC distances over time were found in the mandible.

Table 8 shows the percentage of patients with increased CEJ-MBC distance by extent and number of surfaces. All patients have one or more surfaces where the increase exceeds 1mm and 91% have one or more surfaces where it exceeds 4mm. In 27% of all patients an increase of the CEJ-MBC distance of ≥6mm is found at four up to eight surfaces. An increase in the CEJ-MBC distance of ≥8mm is found in 60% of the patients in whom one up to six surfaces are affected.

Table 8. Percentage of patients with bone level changes by size and number of affected surfaces at Endpoint

Increase of CEJ-MBC distance	No of affected surfaces												
	≥1	≥2	≥4	≥6	≥8	≥10	≥12	≥14	≥16	≥18	≥20	≥22	≥24
≥1mm	100	100	99	95	89	82	72	59	44	30	19	9	5
≥2mm	97	95	84	63	41	20	11	8	2	1			
≥3mm	95	87	68	38	18	7	4	1					
≥4mm	91	84	57	22	9	3							
≥6mm	82	71	27	7	1								
≥8mm	60	36	8	1									

Discussion

Given the large number of children and adolescents who receive orthodontic treatment worldwide and the even larger number, who may receive it in the future, if and when resources will permit, its probable side effects ought to be evaluated both in the short- and long-term perspective.

One side effect – root shortening – was observed almost a hundred years ago (Ottolengui 1914). Since then it has received considerable attention in the orthodontic literature. Nevertheless, an ad hoc review group appointed by the Swedish Council on Technology Assessment in Health Care (2005) was only able to find eight scientific studies on root resorptions considered to represent at least medium high evidence.

Another possible side effect of orthodontic treatment – marginal bone loss – has received considerably less attention and the above mentioned review group was only able to identify two studies representing medium high and one representing high evidence. The focus of the research on marginal loss has been limited to what may occur at proximal, mostly posterior, tooth surfaces.

With the advent of cone beam computed tomography (CBCT) one may presume that the above-mentioned side effects can be studied with better accuracy and precision than hitherto possible and, thus, pave the way for research results of higher evidence. However, there are large technical differences between different CBCT units and considerable differences in the radiation doses that the patients will receive depending both on machines and how they are used.

Factors influencing image quality in CBCT

Several factors can influence the ability to visualize minor structures in CBCT images, particularly spatial resolution, contrast resolution, and noise. Higher spatial resolution becomes possible with smaller voxel sizes but at the expense of an increase in quantum noise unless higher radiation doses are used. Noise also increases with larger FOVs because more scatter radiation is produced. The use of FOVs that do not exceed the area of interest will reduce the amount of scatter radiation, enhance image quality, and reduce the radiation dose to the patient compared with if larger FOVs are used. Hence, the use of an FOV of 60mm x 60mm in all studies on which this thesis is based.

Because the voxel only can present one level of gray the presence of structures of different densities within the extent of the voxel will result in their averaging. Thus, a small structure of high density, such as a thin bone plate, can be averaged out by adjacent structures of lower densities. The phenomenon is called partial volume averaging and increases with larger voxel sizes, as pointed out by e.g. Molen (2010) and demonstrated by Sun et al. (2011). The latter found that a decrease in voxel size from 0.4mm to 0.25mm improved measurement accuracy. In all studies described in this thesis an isotropic voxel of size 0.125mm was used, thus decreasing the risk of averaging out thin bony structures. The CBCT unit used has been found to be superior to many other CBCT machines for the identification of minor anatomical structures (Liang et al. 2010).

With contrast being defined as the differences in the level of gray of parts of the image that correspond to anatomically or physiologically different parts of the examined body, contrast resolution describes how many gray level values that can be displayed. The systems' gray scale depth therefore determines the contrast resolution in digital images. Even though the human eye only can differentiate between a small number of gray values simultaneously, different window settings will allow the utilization of the entire spectrum of gray level values (Kimpe & Tuytschaever 2007).

Other factors influencing image quality are patient movements during exposure and presence of metal objects, such as orthodontic braces and metal fillings. With a firm chin rest and the use of a combined forehead and neck support (Figure 5), the risk of patient movement will be minimized.

Evaluation of diagnostic imaging methods

When adopting a new technique to be implemented in clinical practice and research one ought to evaluate its performance relative to the specific tasks to be solved. Fryback (1983) and Fryback & Thornbury (1991) have described a hierarchy of levels at which a diagnostic imaging method can be evaluated. At the lowest level technical efficacy, such as resolution, noise, and radiation doses, is evaluated. A second level is concerned with diagnostic accuracy efficacy, expressed as e.g. sensitivity and specificity, and area under the ROC-curve. At higher levels diagnostic thinking efficacy is evaluated and at still higher levels patient outcome efficacy and societal efficacy.

The initial studies in this thesis belong to the lower levels of this hierarchy. A method with low efficacy at lower levels may have no value at higher ones and, thus, studies of possible side effects of a specific treatment must be based on methods that can describe the incidence and severity of such effects with a high degree of accuracy. Improved knowledge of side effects to orthodontic treatment may have implications on both patient and societal levels.

Measurement accuracy and precision (Study I-II)

Reformatting of image data from cone beam computed tomography to tomographic views in axial, coronal and sagittal planes can be performed either by utilizing the inherent program at the CBCT workstation, or a third-party program at a PACS workstation to which a stack of original images has been imported. The reformatting then resembles that in computed tomography (CT) in which images in different planes are obtained from a stack of axial slices, an action that usually leads to some image degradation. The use of a PACS workstation may have practical benefits such as the possibilities of real-time reconstructions when this is not possible at the CBCT workstation. It was therefore considered of interest to evaluate the measurement accuracy and the possible implications of different object positioning when using different reconstruction techniques.

Studies of measurement accuracy in CBCT images have been made in various ways. The vast majority of researchers have used skull materials and measured distances either between different anatomical landmarks or between inserted high contrast objects. Others have used artificial objects with known distances between measuring points. The use of skull materials may be considered beneficial in that it can mimic a clinical situation with the presence of e.g. scatter radiation and attenuation from surrounding anatomical structures. However, there is a risk that the results not only represent the accuracy of the method itself but also the individual observer's ability to identify a particular anatomical landmark. The radiographic reproduction of many of those can be more or less distinct and, therefore, subject to observer uncertainties. When an artificial object with distinct markings, these uncertainties are reduced but so is the resemblance with a clinical situation. To minimize factors that could cause problems in the measurement procedures, unrelated to the technique itself, a Plexiglas object with incorporated metal balls was used.

Lascala et al. (2004) measured distances between small metal balls inserted in dry skulls and found distances between them to be underestimated with the CBCT technique used (NewTom 9000, Quantitative Radiology srl, Verona, Italy). Lou et al. (2007) ascribed this to difficulties in identifying the exact mid-point of the balls not only in the radiographs but also when establishing the “gold standard” values. *Study I* may suffer from the same weakness since metal balls were used. However, these were incorporated in individual Plexiglas plates that could be removed from their enclosing when establishing the “gold standard” values. Therefore, it seems likely that these values are subjected to less error than if they would have been measured between metal balls in a skull. The findings in *Study I* are well on par with other studies whether performed on artificial objects (Mozzo et al. 1998, Marmulla et al. 2005, Pinsky et al. 2006, Eggers et al. 2008, Loubele et al. 2008) or skull materials (Kobayashi et al. 2004, Lascala et al. 2004, Loubele et al. 2006, Ludlow et al. 2007, Stratemann et al. 2008).

The mean differences between “gold standard” and radiographic measures, obtained at the PACS workstation, ranged between -0.08mm and -0.13mm. This was only slightly larger than those found at the Accuitomo workstation (-0.08mm to -0.09mm) justifying the use of the PACS station in subsequent clinical studies.

It has only been possible to find one study on the accuracy and reliability of root length measurements using a CBCT technique (Sherrard et al. 2010). In that study 7 fresh porcine heads were scanned (i-CAT, Imaging Sciences International, Hatfield, Pa, U.S.A.) using three voxel sizes (0.2, 0.3 and 0.4mm). Root length measurements were also made in periapical radiographs and found to be underestimated by an average of 2.6mm. In CBCT images they were slightly overestimated (0.17mm - 0.30mm). The difference between the techniques was attributed to difficulties in identifying the CEJs in the periapical radiographs. In our study (*Study II*) the mean differences between direct and radiographic measurements of root lengths were somewhat larger. However, for the vast majority of front teeth the differences were smaller than 1mm. The precision (measurement error) of the method for assessment of root length in patients (0.19mm-0.32mm) is comparable to that presented by Sherrard et al. (0.30mm-0.36mm) who used the same mathematical formula for determination of the measurement error. The measurement errors were more pronounced at the 6-Month examination than at Baseline and Endpoint. It may be due to a initial remodeling making the apical part of the roots more diffuse but also owing to artifacts, caused by the presence of brackets, making the CEJ harder to identify.

In studies utilizing periapical radiography the measurement error of tooth/root length determinations has been reported to range between 0.14mm-0.70mm (Levander et al. 1994, Mirabella & Årtun 1995, Mavragani et al. 2000, Årtun et al. 2005). In general, smaller errors are found for total tooth length measurements and larger for root length measurements. This may reflect the difficulties in identifying the CEJ.

The crucial points in root length measurements in periapical radiography are the identification of the CEJ (Brezniak et al. 2004a) and the root apex. Both are influenced by irradiation geometry differences between radiographs taken at different points in time but, as suggested above, the CEJ may be subjected to larger variations within and between observers when rereading the same images. In the CBCT images used, reconstructions were made so that the long axis of the root was displayed in coronal and sagittal planes. Therefore, serially taken CBCT images do not suffer from the problems that are inherent in central projection imaging. In addition, in high quality CBCT images the CEJ is easily identifiable, in particular when a combination of scan planes is used. Thus, longitudinal root length measurements can be made with a high degree of reliability in CBCT images of good quality.

With respect to marginal bone level assessments a smaller mean difference between "gold standard" values and radiographic measurements (-0.04mm, SD 0.54) was obtained than that reported (1.27mm, SD 1.43) by Mol & Balsundaram (2008) who used NewTom 9000 (Quantitative Radiology srl, Verona, Italy). The variation between surfaces was large (-1.53mm to 1.92mm) but for most of them, individual differences were smaller than 0.5mm. A major factor behind the large variations might be related to difficulties in establishing the "gold standard" values, rather than to inconsistencies in the multiplanar reconstructions. In dried teeth the CEJ can be less well demarcated. Also, the use of a pencil to mark bone crest on the root surface may have induced errors. The measurement error of CEJ-MBC measurements ranged from 0.16mm to 0.31mm at Baseline and from 0.24mm to 0.29mm at Endpoint. Hence, it seems reasonable to assume that reliable comparisons between Baseline and Endpoint data can be made.

Root resorptions in patients (Study III)

During orthodontic treatment forces from the orthodontic appliance cause a resorption of the bone on the pressure side of the alveolar wall, whereas at the other side of the root, the tension side, an apposition of bone occurs. Resorption and apposition of bone is caused by osteoclast and osteoblast activity, regulated by different inflammatory mediators as a response to the pressure stimulus. This process may also affect the root surface, inducing resorption. This can be assumed to occur at any surface of the root emphasizing the use of a three-dimensional technique for its assessment.

No prospective studies have been found that have investigated the incidence and severity of orthodontically induced root resorptions by means of a high quality three-dimensional radiographic technique in a large and homogeneous patient material. Baysal et al. (2011), in a retrospective study, used CBCT (i-CAT, Imaging Sciences International, Hatfield, Pa, U.S.A.) for the evaluation of root resorption at posterior teeth following treatment with rapid maxillary expansion. In 25 patients pre- and post-treatment root volumes of upper premolars and first molars were calculated after segmentation of the CBCT data. Following treatment all roots showed a statistically significant decrease in root volume. The largest mean volume loss was found for the mesiobuccal root of maxillary first molars (18.60mm^3). This volume is equivalent to that of a cube with a side of 2.65mm, that is, it represents a considerable loss of root substance. This way of presenting root resorption data is new and results in difficulties when making comparisons with results of other studies. Compared to commonly used linear measurements it represents a more comprehensive way of demonstrating root resorption data and may be used more often in the future. In which way the extent of root resorptions should be presented depends on the need among orthodontists. Also, different measures may have to be used for clinical versus scientific purposes.

Incidence and severity of root resorptions

The radiographic imaging techniques previously used in root resorption research are periapical radiography, panoramic radiography and, in some cases, lateral cephalometric radiography, with periapical radiography being the most commonly used. Besides variations in imaging techniques, different measures have been used. Some have used scoring systems, that is, ordinal scales, while others have used interval scales, presenting the results either as root shortening in mm or as a percentage of root length. In addition, results have been presented either on the patient or the tooth/root level. These differences may explain the variations in reported incidence on the patient level (0.5% to 100%) as shown in a review by Brezniak & Wasserstein (1993a) comprising articles from 1927 to 1989. Table 9 summarizes the findings from some previous studies on incidence and severity of root resorption, together with information about, for example, sample size, treatment type, and radiographic technique/s.

Compared with many other studies on orthodontically induced root resorption (OIIRR) *Study III* is based on a more homogeneous patient sample in terms of age, type of malocclusion, and treatment type. Because of this and the above mentioned methodological differences it is difficult to make direct comparisons with previous studies on root resorptions and percentage of affected teeth. This problem has been addressed by Brezniak & Wasserstein (1993a) and by Weltman et al. (2010). The latter, for example, emphasized the use of standardized methods and measurement techniques in root resorption studies.

Disregarding differences between studies the results of *Study III*, on the patient level, reveal a somewhat lower incidence (94% of patients with root shortening ≥1mm on ≥1teeth) than previous studies (Table 9) that have reported incidences in the range of 96% to 100% (DeShields 1969, Goldson & Henrikson 1975, Odenrick & Brattström 1983, Preoteasa et al. 2009). These differences may be due to differences in how root resorptions have been assessed. Most of the above mentioned studies used scoring systems and, in some, even an irregular root contour was registered as root resorption. Compared with the results by Årtun et al. (2005), who found root shortening exceeding 2mm in one or more teeth in 20% of the patients, our findings reveal an incidence more than twice as high (50%), using the same threshold value. Our results also show a higher incidence (7%) of patients with the most severe root resorption (≥4mm) than

Table 9. An excerpt of root resorption data from previously published articles

Reference (Year)	Study	Patients (n)	Male/Female (n)	Mean age (yrs)	Malocclusion	Treatment	Extraction (Y/N)	Treatment duration (months,SD)	Teeth examined	Imaging method	Measure	Patients with resorption (%)	Teeth with resorption (%)	Root shortening
DeShields (1969)*	Retro	52	24/28	12.38	Angle II:I	Fixed (1 type)	N	21.6±5.2	12, 11, 21, 22	IO	Score 0-5	99	83	2.19-2.25 (mean grade)
Goldson (1975)*	Retro	42	17/25	13.6	Angle I, II	Fixed (1 type)	Y	19.8±5.1	15, 13, 12, 11, 21, 22, 23, 25, 45, 43, 42, 41, 31, 32, 33, 35	IO	Score 0-8	100	53-95	-
Odenrick (1983)*	Prosp	42	-	13-15	-	Fixed (not spec)	-	-	13, 12, 11, 21, 22, 23	IO	Score 0-7	100	Unclear	-
Beck (1994)*	Retro	83	41/41	14.5	Angle II:I	Fixed (2 types)	Y	32±15	16, 15, 12, 11, 21, 22, 25, 26, 46, 36	LAT/PAN	Score 0-5/Interval scale		5-62	1.1-2.1mm
Hendrix (1994)*	Retro	153	74/79	14.7	-	Fixed (1 type)	Y/N	21±7	15, 13, 23, 25, 46, 45, 43, 33, 35, 36	PAN	Interval scale	-	56-96	0.13-2.8mm
Blake (1995)*	Retro	63	28/35	13	-	Fixed (2 types)	Y/N	20.8±4.5	12, 11, 21, 22, 42, 41, 31, 32	IO	Interval scale	-	-	5.9-12.5% of root length
Taithongchai (1996)*	Retro	400	100/0	14,9	-	Fixed (3 types)	-	20.9±8.4	11, 21	IO	Interval scale	-	-	2.04mm
Mavragani (2002)*	Retro	80	42/38	12.7	Angle II:I	Fixed (1 type)	Y	-	12, 11, 21, 22	IO	Interval scale	-	-	1.78-1.93mm
Årtun (2005)	Prosp	302	83/164	19.2	-	Fixed (not spec)	-	12.4±1.0	12, 11, 21, 22	IO	Interval scale	20.2 (≥1 tooth >2mm)		0.76mm
Mohandesan (2007)	Prosp	40	16/24	15	-	Fixed (2 types)	Y/N	-	12, 11, 21, 22	IO	Interval scale	-	100	1.67mm
Apajalahti (2007)	Retro	601	253/348	11	Angle I, II:I, II:II, III	Fixed (not spec)	Y/N	36±18	All (except 3:rd molars)	PAN	Score 0-2	56	-	-
Pandis (2008)	Prosp	96	29/67	13.02	-	Fixed (not spec)	Y/N	26.4±6.3	12, 11, 21, 22	PAN	Interval scale	-	-	1.30mm
Ramanathan (2009)	Prosp	49	20/29	14.05	-	Fixed (3 types)	-	6 (observation period)	11, 21	IO	Interval scale	-	13-53 (>0.5mm)	0.25-0.46mm
Preoteasa (2009)	Retro	50	10/40	12	Angle I, II, III	Fixed (not spec)	-	28	11/21, 12/22, 13/23, 41/31, 42/32, 43/33	PAN	Score 0-3/Interval scale	96	76.7	
Marques (2010)	Retro	1049	468/581	12.1	Angle I, II:I, II:II, III	Fixed (not spec)	Y/N	-	12, 11, 21, 22, 42, 41, 31, 32	IO	Score 0-4	14.5 (>1/3 root length)	-	-
Huang (2010)	Retro	52	16/36	15.6	Angle I, II	Fixed	Y	-	12, 11, 21, 22, 42, 41, 31, 32	PAN	Interval scale	-	-	0.22-0.58mm
Brin (2011)	Retro	24	5/19	12.4	Angle I, crowding	Fixed (1 type)	Y	16±8.7	11/21	LAT	Interval scale	-	-	1.8-2.1mm

* Included in the SBU-report (2005)
IO; Intraoral (periapical) radiography. PAN; Panoramic radiography. LAT; Lateral (Cephalometric) radiography

that found by Årtun et al. (5%). These differences may be due to differences in radiographic technique and number of tooth groups investigated.

With respect to the incidence of root shortening at the tooth/root level, our results (55% - 91% of roots with shortening >0mm) are similar in range with that reported by Goldson & Henriksson (1975) and Hendrix et al. (1994). However, one should bear in mind that Goldson & Henriksson used a score system and Hendrix et al. based their evaluations on panoramic radiographs.

The maxillary lateral incisor showed the highest frequency of shortened roots and was also, together with the maxillary central incisor and the palatal root of the maxillary premolar, the tooth with the most extensive root shortening. That the maxillary lateral incisor is more prone to root shortening during orthodontic treatment is supported by previous studies (DeShields 1969, Blake et al. 1995, Årtun et al. 2005, Mohandesan et al. 2007, Preoteasa et al. 2009). It has been suggested that this is due to the design of the orthodontic appliance used in extraction cases (Blake et al. 1995). Others have related it to often slender and curved apical part of this tooth (Årtun et al. 2005). Beck & Harris (1994), however, found the central incisor to be the most commonly affected tooth while others have reported no or only small differences between the central and lateral incisor (Mavragani et al. 2002, Pandis et al. 2008). In general, the maxillary incisors followed by the mandibular ones have been reported to exhibit a high incidence and severity of root resorption (Weltman et al. 2010), which is in line with the results of *Study III*. However, Goldson & Henriksson (1975) as well as Preoteasa et al. (2009) reported the highest incidence for the mandibular incisors. In *Study III*, a high incidence of severe root resorption was found in maxillary premolars, which has also been demonstrated by Beck & Harris (1994) and Apajalahti & Peltola (2007). It has been suggested that the extraction of a premolar will increase the root resorption in the remaining, neighboring one, due its significant movement relative to that of other teeth (Beck & Harris 1994) and the longer treatment time in extraction cases (Jiang et al. 2010).

Slanted surface resorptions were mostly found at buccal and palatal root surfaces. This is a significant finding since these surfaces are not displayed in intraoral or panoramic radiographs and because such resorptions eventually may result in root shortenings. One can assume that their presence at the apical part of the root is directly related to the higher pressure that this part is subjected to during tipping movements. This may also explain the relatively high incidence among upper front teeth since those are subjected to more tipping movements during treatment than are other teeth. This hypothesis is supported by the finding made by Wehrbein et al. (1994) who found histological evidence for slanted surface resorptions at a maxillary incisor of a deceased woman who had underwent orthodontic treatment. They related this finding to torque movement, creating a pressure zone at the apical part of the palatal surface.

After approximately 6 months of active treatment, few teeth showed root shortenings exceeding 2mm (0.5% - 4.5% depending on tooth group) and none that exceeded 4mm. Smale et al. (2005) investigated root shortening of the maxillary central and lateral incisors six months after treatment start and found an incidence about twice as high (3% and 4%, respectively) than that found in *Study III* (2% and 1.5%, respectively). There are, however, difficulties in making direct comparisons as their results were reported as scores.

It has been suggested that the amount of resorption at an intermediate control may serve as an indicator for further resorption (Levander et al. 1998, Årtun et al. 2005, Smale et al. 2005, Årtun et al. 2009). The multivariate analysis conducted in *Study III* revealed that root length at 6-Month control was a strong predictor for the severity of root resorption at Endpoint. Hence, this finding is well on par with previous statements.

Goldson & Henriksson (1975), who investigated incidence and severity of root resorptions during three different phases of active treatment, found an increase of root resorptions between an intermediate radiographic control and one at the end of treatment. They suggested that this was caused by the entering into a different treatment phase with uprighting and torqueing of teeth. The findings from *Study III* of a higher monthly rate of resorption after the 6-Month control may be seen as supporting their suggestion. However, if it is the entering into a new, more active treatment phase that is the cause of the increase of root resorption the predictive power of the data from the 6-month control *per se* is at least somewhat illusive on the individual level.

In a univariate analysis it was found that age at Baseline, jaw, tooth group, and root length at 6-Month all had statistically significant effects on the amount of root shortening at Endpoint. Taithongchai et al. (1996) and Mavragani et al. (2002), in accordance with our findings, suggested that younger patients exhibit less severe root resorptions than do older ones. However, Beck &

Harris (1994) and Hendrix et al. (1994) found no such relationship. Årtun et al. (2009) found no correlation between age and root resorption except for the lateral maxillary incisor in which root resorption was less severe the younger the patient. When factors, shown to have a significant effect in the univariate analysis, were included in a multivariate model the effect of age was found not significant. Only jaw, tooth group and root length at 6-Month were related to the degree of root resorption at Endpoint.

Upper jaw teeth are more prone to severe root resorptions than lower jaw teeth. Lateral incisors, central incisors, and canines, in that order, exhibit more severe root resorptions than do other teeth. These findings are not new (Goldson & Henrikson 1975, Brezniak & Wasserstein 1993b).

Neither gender, nor treatment duration or root length at Baseline were significantly related to the degree of root shortening at Endpoint. As regards gender this is in agreement with previous studies (DeShields 1969, Beck & Harris 1994, Hendrix et al. 1994, Blake et al. 1995). That treatment duration did not seem to influence the degree of root resorption seen at Endpoint is in accordance with studies by Beck & Harris (1994), Hendrix et al. (1994), Mavragani et al. (2002) and Årtun et al. (2009). However, other studies have reported such a relation, although weak (DeShields 1969, Taithongchai et al. 1996). With respect to root length at Baseline Årtun et al. (2009) found that, the longer the upper lateral incisor, the more root shortening.

It has been suggested that radiographic examinations should be conducted either after three or six months of active treatment (Levander et al. 1998) or during each three-month period (Hollender et al. 1980). This would make it possible to identify patients at risk of severe root shortening and initiate measures to prevent it or at least minimize it. Based on the results from *Study III* it seems valid to conduct a radiographic examination of the maxillary incisors some time after the start of active treatment. However, the findings of an increased monthly rate of resorption and a dramatic increase in the number of resorbed teeth from the 6-month control to Endpoint may justify its postponement, for example, another three months.

Marginal bone changes in patients (Study IV)

Hitherto, due to the lack of appropriate radiological methods, the focus on marginal bone level changes that might occur during orthodontic treatment has been directed towards the proximal surfaces of the posterior teeth. Since the orthodontic movement, especially of anterior teeth, mostly occurs in antero-posterior directions it may be argued that the marginal bone level at buccal and palatal/lingual surfaces should attract the same or more interest as those of proximal surfaces. The advent of high quality three-dimensional techniques, enabling imaging of thin bone plates, may permit a redirection of research into previously untouched terrain.

Marginal bone level – Baseline

As regards what shall be considered "normal" marginal bone levels and a normal occurrence of dehiscences and fenestrations, most current knowledge emanates from studies of skull materials and from epidemiological studies. Results from large skull materials have been considered to represent the anatomical "ground truth". However, one must keep in mind that such studies often have been conducted on skull materials from previous centuries not necessarily representative of modern populations. The wide age span, with a dominance of older individuals, as well as possible post-mortem changes must also be taken into consideration when evaluating the results.

Epidemiological studies using radiographic techniques usually have focused on the marginal bone level at posterior proximal surfaces. Most commonly, a distance of >2mm between the cemento-enamel junction (CEJ) and the marginal bone crest (MBC) has been used as a threshold value to define a bone level outside a normal range (Källestål & Matsson 1989). However, threshold values between 1-3mm can be found in different studies (Jenkins et al. 1992, Papapanou & Lindhe 2008). In a review of epidemiological studies of periodontal disease in children and adolescents (age 14-16 years) in Scandinavia, Jenkins & Papapanos (2001) reported a prevalence of marginal bone loss of 1.0% to 11.3%, using a threshold level of >2mm. Few individuals had more than two affected sites. Thus, in approximately 89% to 99% of the subjects the marginal bone level was found at a position ≤2 mm from the CEJ at posterior, proximal tooth surfaces. The participants were considered representative of a normal population in the selected age range. Consequently, also individuals in need of orthodontic treatment must have been included. In *Study IV*, the prevalence of posterior tooth surfaces with a CEJ-MBC distance >2mm ranged from 2% (mesial and distal surfaces, lower first molar) to 16% (distal surface, upper first molar). Disregarding the latter, the results are in the lower part of the range reported by Jenkins & Papanos (2001).

It may be argued that adolescents in need of orthodontic treatment differ from other adolescents in respect to the CEJ-MBC distance. However, no statistically significant differences were found between a group of adolescents about to undergo orthodontic treatment and a control group when Bondemark (1998) used posterior bitewing radiographs to measure the CEJ-MBC distance at proximal surfaces. In *Study IV* the mean distance CEJ-MBC for proximal surfaces at the posterior teeth varied between 1.1mm (mesial and distal surfaces of lower first molar) to 1.6mm (distal surface upper first molar) with relatively large variations among the individuals. These distances are larger than those presented by Bondemark (1998) (test group: 0.8-1.0mm for upper and 0.6-0.8mm for lower surfaces). This may reflect the differences between bitewing radiography and CBCT in their abilities to disclose the CEJ-MBC distance.

Recently, there has been an interest within the research community to use CBCT to evaluate more delicate anatomical structures, such as the buccal and palatal/lingual bone plates. Evangelista et al. (2010) investigated the presence of dehiscences, defined as a CEJ-MBC distance of >2mm, on buccal and lingual surfaces in Class I (mean age 27.1 years) and Class II (mean age 26.5 years) patients using an i-CAT CBCT unit. Dehiscences were most common at maxillary canines and first molars, and mandibular lateral incisors, canines and first premolars. They were more frequent at buccal root surfaces than at lingual, except for at the mandibular central incisors where no difference was found between these surfaces.

Using the same type of CBCT as Evangelista et al., Yagchi et al. (2011) in a study of patients aged 18-30 years with Angle class I, II and III malocclusions, found dehiscences to be more prevalent in the mandible than in the maxilla and at buccal surfaces. Independent of type of malocclusion, dehiscences were most often found at front teeth. They found no statistically significant difference in their prevalence between Angle classes.

The findings in *Study IV* are similar to those from the above two studies as regards the prevalence and location of alveolar defects among orthodontically untreated subjects as it also revealed high frequencies of CEJ-MBC distances >2mm and that, with the exception of the mandibular central incisor, buccal surfaces were more affected than lingual ones.

Among proximal root surfaces at anterior teeth, the upper lateral incisor showed the largest percentage of surfaces with a CEJ-MBC distance of >2mm (mesial surface 39%, distal surface 56%). For other front teeth the prevalence of a distance >2mm varied between 8% and 39%. It seems unlikely that all these surfaces would suffer from marginal bone loss due to periodontal disease. Instead, it is more probable that the normal CEJ-MBC distance for many anterior proximal tooth surfaces is larger than the cut-off value for marginal bone loss used for posterior proximal surfaces.

Little is known about what happens to the marginal bone during orthodontic treatment. However, it may be anticipated that an already inadequate bone support may be a complicating factor when performing tooth movements. Thus, with the knowledge of its presence and distribution in the dentition the effect of orthodontic treatment on the marginal bone level may be better understood.

Marginal bone level changes – Baseline to Endpoint

Most studies aimed to investigate the association between orthodontic treatment and marginal bone height differences have used bitewing radiography, limiting the assessment to what occurs at posterior proximal surfaces. In general, these studies conclude that treated subjects show statistically significantly larger increases in the CEJ-MBC than untreated ones. Although differing between studies (Zachrisson & Alnaes 1974, Hollender et al. 1980, Aass & Gjermo 1992, Bondemark 1998, Janson et al. 2003) they have been of limited extent. The findings from *Study IV* confirm that statically significant changes in marginal bone level at these surfaces occur, but that they are small.

Marginal bone level differences at buccal and palatal/lingual surfaces, particularly at front teeth, can be considerably larger than at proximal surfaces as found in *Study IV*. The lingual surfaces of the mandibular front teeth are subjected to the largest changes in CEJ-MBC distances during the course of orthodontic treatment. This was also found in a CT study by Fuhrmann (1996).

In a recent study by Garib et al. (2010) aimed to report and discuss the implications of alveolar bone morphology as visualized by CT examinations, it was concluded that the alveolar bone morphology constitutes a limiting factor for the orthodontic movement and should be individually considered. In this perspective it is interesting to note that surfaces with the largest CEJ-MBC distances at Baseline did not show larger changes of those distances during orthodontic treatment than did surfaces with smaller CEJ-MBC distances at treatment start. Thus, how to use pre-treatment information to individualize orthodontic treatments is still an open question. Evidently pre-treatment marginal bone height is not the only factor to take into account.

Using a combination of laminography (conventional tomography) and standardized occlusal radiography, Mulie & Ten Hoeve (1976) investigated the limitations of tooth movement within the area of the mandibular symphysis. Their findings revealed that if the root came in contact with the lingual cortical bone plate the tooth movement was arrested. If greater forces were applied the cortex did not show any significant remodelling. Instead, the lingual wall became perforated or a dehiscence was created. Handelman (1996) suggested that the cortical plates of the alveolar bone at the apical part of mandibular incisors constitute the anatomical limits and may be considered as the "orthodontic walls", suggesting that challenging these boundaries may cause iatrogenic sequelae. This may explain the findings in *Study IV* of a lack of a clear-cut relation between the marginal bone level at Baseline and at Endpoint.

It may be argued that the marginal bone level changes found in *Study IV* are not caused by the orthodontic treatment *per se,* but by other factors. One such factor is the continuous tooth eruption during the adolescent period. However, it seems unlikely that this can explain all differences found in the CEJ-MBC distances before and after treatment. Also, the variation in age among the participants explained only a small percentage of the variation in CEJ-MBC distances at Baseline. Another factor is the aggressive form of periodontal disease sometimes encountered among adolescents (Tonetti & Mombelli 2008). However, even in the improbable event that this would not have been detected during the continuous monitoring of the patients' oral hygiene its relatively low prevalence in the adolescent population could only explain a small fraction of the observed changes.

For a study to be characterized as representing high scientific evidence according to the Swedish Council on Technology Assessment in Health Care and other scientific bodies the study should be a randomized controlled trial (RCT). In the present study no control group, that is, no randomized sample of untreated adolescents with the same type of malocclusion and an equivalent follow-up period has been used for comparison. Not only would this be questionable from an ethical point of view. Its necessity can also be questioned for the following reasons. Each individual has been its own control and factors other than the orthodontic treatment itself can be ruled out other than to a very limited extent. Therefore, it can be argued that the existence of a cause-effect relation between the orthodontic treatment and the presented results is indisputable despite the lack of a control group. That is not to say that RCT studies are not mandatory when, e.g. comparing the results of different treatments.

With respect to factors related to the radiographic technique itself, it may be argued that the increase found in CEJ-MBC distance could be related to the problem in identifying a very thin cortical bone plate due to e.g. the effect of partial volume averaging or the presence of too much noise. However, with the use of a very small voxel size and a limited field-of-view only extremely thin bone plates would go unobserved.

One major question still remains, namely, if the alveolar bone is capable of regeneration to pre-treatment levels. Ten Hoeve & Mulie (1976) suggested that the cortical bone would be regenerated within 6 months, regardless of the extent of the tooth movement. Others have shown that no regeneration occurs (Karring et al. 1982, Sarikaya et al. 2002) at least not until the root has been repositioned in the alveolar bone due to relapse (Engelking & Zachrisson 1982, Karring et al. 1982, Thilander et al. 1983). This is an area that deserves further investigations and for such scientific evaluations the use of high quality CBCT examinations may be well suited.

Future considerations

A high quality CBCT technique offers excellent possibilities for the scientific evaluation of root resorption and marginal bone level changes during orthodontic treatment. There are still areas, technical as well as biological, that need to be further addressed. One is the limit of CBCT in disclosing thin bone plates and what factors that are the limiting ones. A key issue is whether observed marginal bone changes are transitory or not. Another is to what extent slanted surface resorptions precede apical root shortening and whether their presence could be used as a predictor of future root shortening. Still another is to what extent root shortening and decreased marginal bone levels occur in combination and, if so, what implications this will have for the long-term survival of involved teeth.

Conclusions

- Measurements can be made with a high degree of accuracy and precision in CBCT images of high quality.

- Different positioning of the subject, that can occur when CBCT examinations are to be made, has no influence on the results.

- Small, but negligible, distortions can result when tomograms are reformatted by means of a third-party program from a stack of axial slices.

- The use of CBCT with high-resolution images combined with multiplanar reconstructions provides a method for both accurate and precise assessments of root length and marginal bone levels.

- Most patients and teeth show some degree of root shortening after orthodontic treatment.

- Few factors, other than already known ones, have a statistically significant effect on the degree of root shortening.

- The monthly rate of root resorption is larger after six months of treatment than during preceding months.

- Slanted surface resorption is frequent at palatal root surfaces, surfaces that only can be evaluated using a tomographic technique.

- There are large differences in the distances between the cemento-enamel junction and the marginal bone crest among teeth and tooth surfaces in adolescents prior to orthodontic treatment, particularly at buccal and lingual surfaces.

- During the course of orthodontic treatment large decreases of marginal bone height can occur at buccal and palatal/lingual surfaces of front teeth but smaller at most proximal surfaces.

- Age and treatment time do not have a statistically significant influence on the degree of marginal bone level changes during orthodontic treatment.

- Decrease of marginal bone height is larger in the mandible than in the maxilla and larger in girls than in boys with respect to palatal/lingual surfaces.

- High quality CBCT examinations can be a valuable tool in future orthodontic research.

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