The outcome of root-canal treatments assessed by cone-beam computed tomography
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Clinical endodontics has been defined as prevention and/or elimination of apical periodontitis (AP) (Ørstavik & Pitt Ford 1998, Friedman 2002, Trope 2003, Wu et al. 2006). Accordingly, the aim of root canal treatment is to minimize the burden of root (canal) infection and achieve absence of AP. Clinical outcome studies constitute an important part of endodontic research. The clinical decision on the prognosis and treatment options is based on outcome studies that provide essential information to the patient and dentist (Friedman et al. 2003, Patel 2009, Wu et al. 2009a, 2011). Outcome studies also provide evidence to identify the best treatment protocol (Ng et al. 2007).

**Radiographic assessment of outcome**

Periapical radiography (PA) has been utilized to assess the outcome of treatment for nearly 100 years (Patel et al. 2011). Radiographic assessment is essential to determine the outcome (Ng et al. 2007) as many teeth, including those with lesions, are asymptomatic at recall. In some outcome studies, absence of radiolucency at recall represented treatment success and the percentage of absence of radiolucency was the reported success rate; in some studies, both absence and reduction of radiolucency were considered as success (Friedman et al. 2003, Ng et al. 2007, 2011). However, a recently published review by SBU (Swedish Council on Health Technology Assessment), summarizing literatures from 1950 to 2011, concluded that the accuracy of PA for identifying the presence/absence of bone tissue lesions and monitoring the changes over time is limited (Petersson et al. 2012).

When a bone lesion is within the cancellous bone and the overlying cortical bone is substantial, the bone lesion may not be visible on PA (Bender & Seltzer 1961, Bender 1982, van der Stelt 1985, Huimonen & Ørstavik 2002). Cone-beam computed tomography (CBCT) detected pretreatment periapical lesions in 10% more teeth with irreversible pulpitis than PA (Abella et al. 2012). PA may not reveal the change of these undetectable lesions after treatment. Furthermore, PA detected post-treatment periapical lesions in 20-39% less teeth than CBCT (Lothag-Hansen et al. 2007, Low et al. 2008, Christiansen et al. 2009, Moura et al. 2009, Bornstein et al. 2012, Patel et al. 2012a). It appears that PA may under-estimate the incidence of AP before and after

More than half of the periapical lesions have a larger buccal-lingual diameter, which could be 2 times as large as the mesio-distal diameter (Lofthag-Hansen et al. 2007). The size and change of lesions in buccal-lingual direction may not be revealed correctly by PA (Paula-Silva et al. 2009).

The percentages of absence and reduction of radiolucency could be over- or underestimated by PA. Accurate and objective information for better understanding of the long-term dynamics of periapical healing becomes challenged. This in turn may influence the pre-treatment and post-treatment diagnosis and treatment strategy (Wu et al. 2006, Abella et al. 2012). Therefore, the outcome of root canal treatment should be reevaluated using more accurate radiographic techniques (Wu et al. 2006, 2009a, 2011).

Quality of root filling assessed by PA
In a systematic review that analyzed the results of 63 outcome studies published between 1922 and 2002 (Ng et al. 2008), four factors were identified as outcome predictors: presence of preoperative periapical lesion, density and apical extent of root filling, and quality of coronal restoration.

Satisfactory root filling was defined as flush fillings (0-2mm within the radiographic apex) without voids on PA. In clinical endodontics, the major apical foramen is an important anatomic landmark. Instrumentation and root filling procedures beyond the apical foramen should be prevented (Bergenholtz et al. 1979). However, in most cases, the apical foramen is not visible on 2-dimensional radiographs and therefore, the radiographic apex has to be used instead, as the apical terminus (ElAyouti et al. 2001). The apical foramen is located up to 3.8 mm short of the apex in the buccal, lingual, mesial or distal aspect of the root (Dummer et al. 1984). Therefore, flush or short root fillings on PA may actually not be flush or short root fillings at all.

Except for the palatal root of maxillary molars, all root canals are wider in their buccolinguinal than mesiodistal view (Wu et al. 2000). This explains the ex-vivo observation that significantly more voids are detected
in buccolingual views (taken with the direction of the x-ray from the mesial to the distal, Fig. 1) (Kersten et al. 1987, van der Sluis et al. 2005, Wu et al. 2009b). This view is obviously not available in the clinic. Therefore, the high density of root fillings appeared on PA in clinical studies is unreliable.

Use of CBCT in endodontics
CBCT has been introduced to the field of endodontics in the 1990s (Wu et al. 2006). A three-dimensional CBCT has higher sensitivity as compared to PA in detecting extra canals (Huurnonen et al. 2006), vertical root fracture (Bernardes et al. 2009, Hassan et al. 2009), dental trauma assessment such as horizontal root fracture, nature and severity of alveolar and luxation injuries (Cohenca et al. 2007, Cotton et al. 2007, Tsukiboshi 2008, Patel 2009), root resorption (Patel et al. 2009), perforations (Shemesh et al. 2011) and post-treatment apical periodontitis (Patel 2009).

CBCT overcomes several limitations of conventional PA, is more sensitive and shows more information in 3-dimension than PA. To date, the accuracy of CBCT-diagnosis has not been adequately investigated (Petersson et al. 2012). The influence of lower spatial resolution and artifacts of CBCT images on the accuracy of diagnosis needs to be studied (Patel 2009). As this new imaging technique involves higher ionizing radiation dose and additional costs, consensus should be reached on the safe clinical use of CBCT (Patel & Horner 2009, AAE & AAOMR 2011).

Objectives of the thesis
The aim of this thesis was to investigate the outcome of root canal treatment and predictors determined by CBCT and the reliability of CBCT-findings. Two approaches were taken:

1. Ex-vivo experiments were performed to assess the accuracy of PA and CBCT in diagnosing the quality of root filling and the presence/absence and size of periapical lesions.

2. The outcome of primary root canal treatments was analyzed using both PA and CBCT in 3 clinical studies, 2 retrospective and 1 prospective. The potential clinical factors were analyzed.
Outline of the thesis

- **In chapter 2** (ex-vivo experiment), extracted teeth with and without simulated unfilled areas were radiographically examined. The ability of PA and CBCT to detect unfilled areas at the buccal and lingual aspects of root filling was compared.

- **In chapter 3** (ex-vivo experiment), bone defects were prepared at the base of extraction sockets of teeth to mimic periapical bone lesions in human mandibles. The physical volume of the lesion (Vp) was used as a gold standard. The accuracy of PA and CBCT in diagnosing the presence/absence and size of periapical lesions was investigated.

- **In chapter 4** (ex-vivo experiment), the length of root canals in teeth in human dentulous mandibles, the distance between the coronal reference point and major apical foramen, was measured with CBCT data. The root canal length measurements performed with CBCT scans were compared with a gold standard.

- **In chapters 5-7** (clinical studies), the outcome of root canal treatments and outcome predictors were analyzed. Primary root canal treatments were performed in teeth with vital pulp (Chapter 5) and teeth with AP (Chapter 6). Both PA and CBCT techniques were used in 3 studies. The effects of additional ultrasonic irrigation on the outcome were observed in Chapter 6. The influence of the quality of root filling on outcome was investigated in Chapter 7.
Two radiographs of a mesial root filled with laterally compacted gutta-percha cones and sealer. Left, The buccolingual radiograph did not exhibit any voids. Right, The mesiodistal radiograph of the same root presented voids. The buccolingual internal diameter (right) was much wider than the mesiodistal diameter (left).
References:


