International Endodontic Journal

doi:10.1111/j.1365-2591.2009.01566.x

Void detection in root fillings using intraoral analogue, intraoral digital and cone beam CT images

B. Huybrechts[1], M. Bud[2], L. Bergmans[1], P. Lambrechts[1] & R. Jacobs[3]

[1]BIOMAT Research Cluster, School of Dentistry, Oral Pathology and Maxillofacial Surgery, Catholic University of Leuven, Belgium; [2]Dentomaxillofacial Radiology Department, Faculty of Dentistry, University of Medicine and Pharmacy Cluj-Napoca, Romania; and [3]Oral Imaging Center, School of Dentistry, Oral Pathology and Maxillofacial Surgery, Catholic University of Leuven, Belgium

Abstract

Huybrechts B, Bud M, Bergmans L, Lambrechts P, Jacobs R. Void detection in root fillings using intraoral analogue, intraoral digital and cone beam CT images. *International Endodontic Journal*, **42**, 675–685, 2009.

Aim To compare void detection in root fillings using different radiographic imaging techniques: intraoral analogue, intraoral digital and cone beam CT (CBCT) images and to assess factors influencing small void detection.

Methodology Two straight root canals in canine teeth were prepared. Calibrated steel wires of five different diameters (200, 300, 350, 500, 800 μm) were inserted respectively in the canal after the injection of a sealer. To simulate filling voids of known dimensions, the wires were removed after the sealer had set. Each sample was imaged, using a Minray X-ray tube (Soredex, Helsinki, Finland) at optimal clinical settings combined with Vistascan PSP (Dürr Dental, Bietigheim-Bissingen, Germany), Digora Optime PSP (Soredex), Sigma CCD (Instrumentarium, Tuusula, Finland) and E-speed films (Agfa-Gevaert, Mortsel, Belgium). The teeth were also imaged using CBCT (3D Accuitomo, Morita, Japan). A generalized mixed model and ANOVA analysis were used on the acquired data (Tukey–Kramer correction).

Results There was no evidence that the factor 'root level' affected void detection in root fillings. 'Void size' was a main determining factor as all voids larger than 300 μm were determined with all techniques. For the smaller voids, there were significant differences between the 5 imaging techniques at different void sizes and different root levels.

Conclusions Void size and imaging technique were main determining factors. Voids larger than 300 μm were determined with all imaging techniques. For small void detection, all digital intraoral techniques performed better than intraoral analogue and CBCT images.

Keywords: cone beam CT, digital radiography, endodontic, root canal, void detection.

Received 21 October 2008; accepted 20 February 2009

Introduction

The ultimate aim of a root filling is to fill the entire prepared and cleaned root canal. In order to prevent post-treatment disease, as many microorganisms as possible should be eradicated and no space should be left for bacteria to populate and proliferate (Lin *et al.* 1992, Wu *et al.* 2006).

The importance of the presence and size of voids in root filling materials is unclear. Their presence in both the apical and coronal parts of the root filling may provide pathways for leakage. This could allow bacterial regrowth, reinfection and culture reversal, leading to post-treatment disease (Peters *et al.* 1995). For voids that extent through the entire root filling the risk of post-treatment disease may be even higher. However, detection of voids or pathways between the apical and coronal part of a root filling is difficult.

Correspondence: Reinhilde Jacobs, Oral Imaging Center, School of Dentistry, Oral Pathology & Maxillofacial Surgery, Catholic University of Leuven, Kapucijnenvoer 7, B-3000 Leuven, Belgium (Tel.: +32 16 33 24 10; fax: +32 16 33 24 10; e-mail: reinhilde.jacobs@med.kuleuven.be).

Many laboratory testing techniques have been developed and used to evaluate the sealing ability and homogeneity of root fillings. Dye penetration, fluid transport and cross-section analyses are valuable techniques but do not always corroborate each other (Greenhill & Pashley 1981, Kersten *et al.* 1986, Van den Berg *et al.* 1993, Wu *et al.* 1993). Furthermore, they do not always correlate with the degree of periapical infection or radiographic homogeneity of the root filling (Pitt Ford 1983, Dummer *et al.* 1994).

Clinical radiographs are minimally invasive and ethically acceptable for evaluating the treatment quality of root fillings. Indeed, careful assessment of the root canal system based on high quality radiographs is a prerequisite for all stages of root canal treatment, including treatment quality assessment (Lavelle 1999, Wallace *et al.* 2001, Sogur *et al.* 2007). For assessment of the homogeneity of root fillings, no digital system has shown better results than intraoral analogue imaging (Sogur *et al.* 2007). Recent studies have demonstrated that intraoral digital image quality approaches that of intraoral analogues, but often only after the application of image processing algorithms (Li *et al.* 2004, Kositbowornchai *et al.* 2006, Sogur *et al.* 2007).

However, it should be noted that high resolution intraoral digital radiographic systems (>12 lp mm^{-1}) have been developed mostly in the last few years. A resolution under 6 lp mm^{-1} offers less information than intraoral analogues (Miles & Van Dis 1993). Digital images have to exceed the potential 50 μm spatial resolution in order to improve the quality of endodontic images (Lavelle 1999). As the resolution of the current digital systems has increased to 16 and even 22 lp mm^{-1}, a detection of gaps in the order of 60 μm should be feasible.

Although the continuing development of digital radiography and image processing has created new opportunities for image quality improvement, it can do little to decrease the superimposition of overlying structures that obscure the object of interest. As clinical radiographs are only two-dimensional (2D) reproductions, the radiographic monitoring of root canal treatment is challenging because of the difficulties in distinguishing features superimposed onto each other (Sogur *et al.* 2007). Filling materials, dentine, cortical and trabecular bone and soft tissues may mask voids in a root filling, even when using the theoretically optimum resolution.

Conventional CT offers 3D images but is less used in endodontics because of its high cost and massive radiation dose required for image acquisition. The recently introduced limited CT for the dental practice is able to resolve a volumetric acquisition of a limited area using a cone beam CT (CBCT) instead of a collimating fan beam technique. This can result in a lower radiation dose, depending on the device used (Guerrero *et al.* 2006). So far, only a few studies have reported on the use of CBCT in endodontics (Stavropoulos & Wenzel 2006, Lofthag-Hansen *et al.* 2007, Sogur *et al.* 2007, Estrela *et al.* 2008, Low *et al.* 2008).

Sogur *et al.* (2007) investigated the subjective image quality difference among intraoral analogue, intraoral digital and CBCT images to score homogeneity of root fillings. This homogeneity, however, was described as 'adaptation to the lateral canal walls' rather than 'voids inside the root canal filling material'. Moreover, Sogur *et al.* (2007) did not mention void size characteristics.

Therefore, this study aims to compare void detection in root fillings using an intraoral analogue, three intraoral digital and a CBCT imaging technique and also determine the influence of void size and root level on the void detection rate.

Materials and methods

Sample preparation

Two extracted human mandibular canine teeth were used. They were stored in a 0.5% chloramine solution, at 4 °C until use. The roots were then circumferentially cleaned and crowns were removed using a slow speed diamond saw (Isomet 1000; Buehler, Lake Buff, IL, USA). Root canal treatment was initiated by removing pulp remnants. After preflaring with GT Accessory Files (Dentsply Maillefer, Ballaigues, Switzerland) the canals were instrumented using System GT Rotary Files in a crown-down sequence up to size 40, .08 taper 5.0 mm beyond the apical terminus. In this way, the apical preparation diameter was approximating 800 μm. Throughout instrumentation, irrigation with a 2.5% sodium hypochlorite solution (NaOCl) was performed using a 27-gauge Monoject needle (Sherwood Medical, St. Louis, MO, USA) and patency was assured. Ultrasonic agitation (P10; Satelec, Merignac, France) and high-volume flushes with 17% EDTA for 5 min, 2.5% NaOCl for 2 min and sterile water were applied for smear layer removal. After drying with paper points, both root canals were filled with Topseal (Dentsply Maillefer, Ballaigues, Switzerland), an epoxy resin sealer with a radio-opacity representative for root filling materials. The two-paste material was mixed

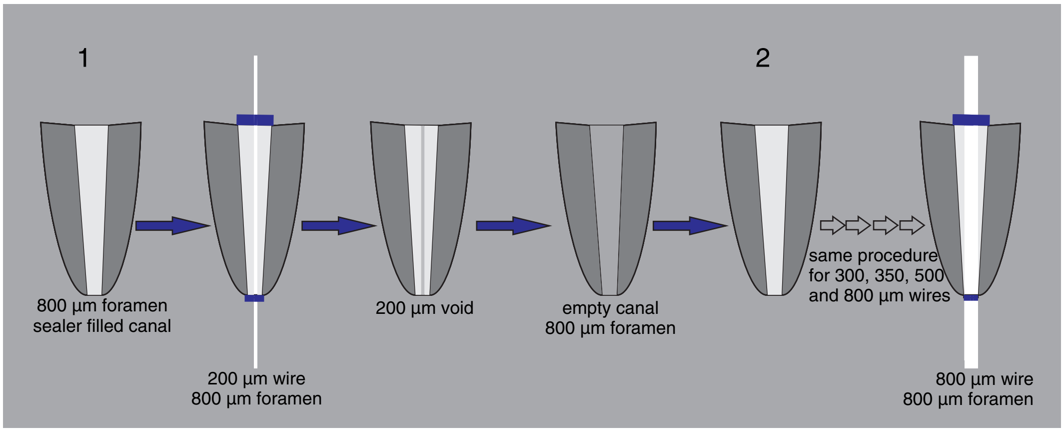

Figure 1 Scheme showing the procedure to create standardized simulated voids.

and introduced via a Skini syringe (Ultradent Products, South Jordan, UT, USA).

Canals were filled by inserting a 27-gauge Monoject needle to the apex and expressing the resin while slowly withdrawing the syringe until Topseal was seen at the coronal orifice. The fillings were completed by fitting a steel wire (200, 300, 350, 500 or 800 µm diameter) from the orifice through the apical foramen. Excess material at both sides was removed with cotton wool. The coronal and apical openings were sealed (Block-out resin; Ultradent Products, South Jordan, UT, USA) (Fig. 1) and radiographs were taken to validate the fillings. The specimens were stored at 37 °C and 100% humidity for 24 h.

Imaging

Mandibular bone and soft tissues were simulated to provide clinical relevance. The two canines were originally collected from different individuals and were not extracted from the mandible used in this study. Mix D (K.U. Leuven laboratory, Leuven, Belgium) was selected as a soft tissue simulator (paraffin wax, polyethylene, magnesium oxide, titanium dioxide) and had the thickness of average cheek and mucosa (0.5–1 cm). The soft tissue tongue simulator was anatomically designed and had a thickness ranging from 3 cm (tongue base) to 1 cm (tongue tip) (White 1977). The root sample was placed in an empty canine socket of a dried mandible after it was covered with the soft tissue simulator. The roots (with root filling and wire) were imaged using 5 different radiographic imaging systems (Sigma CCD, Vistascan PSP, Digora Optime PSP, E-speed film, Accuitomo CBCT). A Minray X-ray tube (Soredex, Helsinki, Finland) was used for acquiring the intraoral radiographic images (DC, 70 kV, 7 mA, 0.08 s for CCD, 0.20 s for PSP and E-speed films) and the 3D Accuitomo (Morita, Japan) was used for the acquisition of the CBCT images (DC, 70 kV, 2 mA, 17.5 s).

After the sealer had set, the smooth 200 µm steel wire was removed in order to simulate a pathway between the apical and coronal part of the root filling (i.e. top-down voids) and then the sample (with root filling and without wire) was imaged again using the 5 different imaging techniques. After imaging, the root was inserted in a glass container filled with chloroform, placed in an ultrasonic bath and left until all the resin sealer had been removed. This was confirmed with parallel and angled radiographs. For the smaller void sizes, System GT rotary files were used without touching any root dentine to provide a path for the chloroform. In this way, root canal morphology was not alternated for the different wire/sealer combinations. This procedure was repeated for the next, thicker wire/sealer combination (Fig. 1). The same radiographic techniques were used for both root samples following all different wire diameters. At the end, the canals were completely filled with resin sealer and imaged as a control.

Void detection

After creating 5 different void sizes (200, 300, 350, 500, 800 µm) in two different extracted canine roots, radiographic void detection was carried out on the images acquired by the 5 different radiographic imaging methods (analogue intraoral radiographs, Digora

PSP, Vistascan PSP, Sigma CCD, 3D Accuitomo CBCT) at 5 different root levels (1, 4, 7, 10, 13 mm short of the apex). The images were numbered and mounted in random order.

Observations were carried out by seven independent observers, all specialized dentists (in either endodontology or oral radiology). The observers were informed that some of the images might show voids within the root filling but were not given information about potential void size differences among different images or different distances to the apex. For each image the observer was asked to indicate whether there was a void visible in the root filling and afterwards at which levels within the root canal it was visible (1, 4, 7, 10, 13 mm short of the apex). The observation time was not limited. This task was carried out by all the observers under the same viewing conditions, in a light-obscured room. For viewing of analogue intraoral radiographs a viewing box was collimated to the size of the actual intraoral film. Films were viewed with a 2× magnification and a sliding calliper. Digital images were presented on a 17 inch screen set at a 32 bit screen resolution, and a viewing distance to the screen of 50 cm. The radiographs on the screen were presented with a 2× enlargement and a black collimation around the image. A digital ruler was used for all root level measurements.

For the analogue and digital intraoral images, void presence was measured at 1, 4, 7, 10 and 13 mm away from the apex. The measuring locations were standardized by horizontal measurements indicators adjacent to the root canal space on the digital ruler or a transparent grid overlaying the analogue intraoral radiograph.

For the 3D Accuitomo images, the slices contained the actual information in the X, Y, Z-axis, which allowed for void presence detection in the selected planes. For the X, Y slices, the selected slice contained the middle portion of the tooth. On these selected 2D images, it was then possible to determine the presence of a void at 1, 4, 7, 10 and 13 mm from the apex. The horizontal sections (Z-axis) were selected at 1, 4, 7, 10 and 13 mm from the apex and on each of these images voids could be determined.

Observer calibration

One individual informed the seven observers about their tasks without indicating the purpose of the study (as above). It was stressed that observers had to score voids within the root filling and not around it. The artefactual burnout phenomena (mach bands, Lane *et al.* 1976) seen on CBCT images around root fillings were explained and the observers were told not to score them as a void. Ten test cases were discussed by one individual with the observers before presenting 10 other test cases to them. All scored these images independently and then the panel of observers discussed their scores and attempted to reach consensus.

Biomedical statistical analysis

A generalized linear mixed model was set up using 'imaging technique', 'observer', 'void size', 'root level' and their respective interaction factors as main effects, while teeth were considered as a random effect. An ANOVA-analysis of the main and interaction effects revealed a significant interaction between 'observer' and 'void size'. A pairwise comparison of observers per void size was then set up. The global significance level was corrected to 0.05 (Tukey–Kramer correction for simultaneous hypotheses).

Another generalized mixed model was set up using 'imaging technique', 'void size', 'root level' and their respective interaction effects as factors, and 'observer' as a random effect. The imaging techniques were compared for each 'void size' – 'root level' combination. Void sizes were compared for each 'imaging technique' – 'root level' combination and 'root levels' for each 'imaging technique' – 'void size' combination. Corrections for simultaneous hypotheses testing were set up (Tukey–Kramer, significance level 0.05).

Results

Observer comparison

The factor 'observer' had a slight interaction with 'void size'. Therefore, observers were compared pairwise per void size. When comparing the observations of all evaluators for void sizes 350, 500 and 800 μm, there were no significant differences ($1.00 > P > 0.91$). This means that the interobserver correlation for big void sizes was perfect. For the 200 μm voids, observer 2 and 7 scored somewhat lower although not significantly ($P > 0.05$) and for the 300 μm voids, there was only little correlation between observers 1 and 3 ($P = 0.02$). Although no perfect correlation, the overall correlation was high. Moreover, the amount of moderately correlating data was very limited and only restricted to the lower void sizes. Therefore, the factor 'observer' was

Table 1 ANOVA table of first, second and third order effects

Effect	
Imaging system	S
Void size	S
Root level	S
Imaging system : Void size	S
Imaging system : Root level	S
Void size : Root level	S
Imaging system : Void size : Root level	NS

S = significant, NS = not significant

Table 2 Void detection percentages related to void size and imaging system

	Void size (μm)					
Imaging system	800	500	350	300	200	Mean
1. Sigma CCD	100.0	100.0	100.0	100.0	100.0	100.0
2. Digora Optime PSP	100.0	100.0	100.0	85.7	78.6	92.9
3. Vistascan PSP	100.0	100.0	100.0	100.0	85.7	97.1
4. Accuitomo CBCT	100.0	100.0	100.0	50.0	28.6	75.7
5. E-speed film IO	100.0	100.0	100.0	85.7	14.3	80.0
Mean	100.0	100.0	100.0	84.3	61.4	89.1

introduced as an extra random variable in the next generalized mixed model.

Comparison of void detection among different void size groups

Void size was a main determining factor (Tables 1, 2 and 3). On the no-void (completely filled canals) images, no observer detected a void. In general, irrespective of root level, the seven observers determined the presence of a void in 89.1% of the images. At 200, 300, 350, 500 and 800 μm these percentages were 61.4%, 84.3%, 100.0%, 100.0% and 100.0% respectively (Table 2). The following comparisons were significant: 200–300, 200–350, 200–500, 200–800, 300–350, 300–500 and 300–800 ($P < 0.001$) (Table 3F). This means that it was more difficult to detect smaller voids than bigger voids in these comparisons.

Taking into account root level differences, the following statistical conclusions could be drawn (Table 3A–E):

1. For all digital intraoral techniques, there was no evidence of significant differences among the void detection rates of the different void size groups at all root levels ($1.00 > P > 0.05$).

2. With the Accuitomo CBCT device, at 1 mm short of the apex, the smallest voids (200 μm) were significantly more difficult to detect, compared with the 350, 500 and 800 μm voids ($P < 0.02$). This was also the case at 10 mm short of the apex ($P < 0.02$). Moreover, at this level 300 μm voids were more difficult to detect compared with 350 μm voids ($P = 0.01$). At 13 mm short of the apex, 200 and 300 μm voids were more difficult to detect, compared with 800 μm ($P = 0.04$, $P = 0.02$ respectively).

3. With analogue intraoral images, at 1 mm short of the apex, 200 μm voids were significantly more difficult to detect, compared with the 350, 500 and 800 μm voids ($0.02 > P > 0.00$). At 4 mm short of the apex, 200 μm voids were more difficult to detect, compared with 300, 350, 500 and 800 μm ($0.05 > P > 0.00$). The same was true at 7 mm and 10 mm short of the apex ($0.05 > P > 0.01$, $0.02 > P > 0.00$ resp.). At 13 mm short of the apex, 200 μm voids were more difficult to detect, compared with 300, 350 and 500 μm ($0.02 > P > 0.00$).

Comparison of void detection among different imaging technique groups

'Imaging technique' was a main determining factor (Tables 1, 2 and 4). Overall void detection percentage on Sigma CCD images was 100.0%, whereas this was 92.9%, 97.1%, 75.7% and 80.0% on Digora Optime PSP, Vistascan PSP, Accuitomo CBCT and analogue intraoral radiographs respectively (Table 2). Significantly more voids were detected with Sigma CCD images compared with Digora Optime PSP, Accuitomo CBCT and analogue intraoral images (all $P \leq 0.0001$). Significantly less voids were detected with Digora Optime PSP images than with Vistascan PSP and Sigma CCD images. However, with Digora Optime PSP images significantly more voids were detected than with Accuitomo CBCT images (all $P < 0.0001$). With Vistascan PSP images, significantly more voids were detected than with Accuitomo CBCT, analogue intraoral and Digora Optime PSP images (all $P < 0.0001$).

In 96.7% of all digital intraoral images (Sigma CCD + Digora Optime PSP + Vistascan PSP) the presence of a void was evident. This was a significantly better void detection rate compared with Accuitomo CBCT (75.7%) and analogue intraoral radiographs (80%) (all $P > 0.0001$) (Table 4F).

800–500–350 μm voids (Table 4C–E)

For void sizes 350, 500 and 800 μm the presence of a void was evident on all images (100.0%) irrespective of imaging technique, thus, there was no evidence for significant void detection differences among the

Table 3 Comparison of void detection among different void size groups

	Root level (mm)						Root level (mm)				
Void size(μm)	1	4	7	10	13	Void size(μm)	1	4	7	10	13
(A) Imaging system 1						(B) Imaging system 2					
200/300	NS	NS	NS	NS	NS	200/300	NS	NS	NS	NS	NS
200/350	NS	NS	NS	NS	NS	200/350	NS	NS	NS	NS	NS
200/500	NS	NS	NS	NS	NS	200/500	NS	NS	NS	NS	NS
200/800	NS	NS	NS	NS	NS	200/800	NS	NS	NS	NS	NS
300/350	NS	NS	NS	NS	NS	300/350	NS	NS	NS	NS	NS
300/500	NS	NS	NS	NS	NS	300/500	NS	NS	NS	NS	NS
300/800	NS	NS	NS	NS	NS	300/800	NS	NS	NS	NS	NS
350/500	NS	NS	NS	NS	NS	350/500	NS	NS	NS	NS	NS
350/800	NS	NS	NS	NS	NS	350/800	NS	NS	NS	NS	NS
500/800	NS	NS	NS	NS	NS	500/800	NS	NS	NS	NS	NS
(C) Imaging system 3						(D) Imaging system 4					
200/300	NS	NS	NS	NS	NS	200/300	NS	NS	NS	NS	NS
200/350	NS	NS	NS	NS	NS	200/350	S	NS	NS	S	NS
200/500	NS	NS	NS	NS	NS	200/500	S	NS	NS	S	NS
200/800	NS	NS	NS	NS	NS	200/800	S	NS	NS	S	S
300/350	NS	NS	NS	NS	NS	300/350	NS	NS	NS	S	NS
300/500	NS	NS	NS	NS	NS	300/500	NS	NS	NS	NS	NS
300/800	NS	NS	NS	NS	NS	300/800	NS	NS	NS	NS	S
350/500	NS	NS	NS	NS	NS	350/500	NS	NS	NS	NS	NS
350/800	NS	NS	NS	NS	NS	350/800	NS	NS	NS	NS	NS
500/800	NS	NS	NS	NS	NS	500/800	NS	NS	NS	NS	NS
(E) Imaging system 5						(F) All systems					
200/300	NS	S	S	S	S	200/300	S				
200/350	S	S	S	S	S	200/350	S				
200/500	S	S	S	S	S	200/500	S				
200/800	S	S	S	S	NS	200/800	S				
300/350	NS	NS	NS	NS	NS	300/350	S				
300/500	NS	NS	NS	NS	NS	300/500	S				
300/800	NS	NS	NS	NS	NS	300/800	S				
350/500	NS	NS	NS	NS	NS	350/500	NS				
350/800	NS	NS	NS	NS	NS	350/800	NS				
500/800	NS	NS	NS	NS	NS	500/800	NS				

S, significant; NS, not significant; imaging system 1, Sigma CCD; 2, Digora Optime PSP; 3, Vistascan PSP; 4, Accuitomo CBCT; 5, E-speed film IO.

5 imaging techniques at all root levels ($1.00 > P > 0.07$).

Only in the smaller void groups (200 and 300 μm) the void detection potential of the 5 radiographic systems differed for certain 'void size'-'root level' combinations.

300 μm voids (Fig. 2) (Table 4B)

Generally (irrespective of root level), for 300 μm voids, the void detection rates were 100.0%, 85.7%, 100.0%, 50.0% and 85.7% for Sigma CCD, Digora Optime PSP, Vistascan PSP, Accuitomo CBCT and analogue intraoral radiographs respectively. With Sigma CCD, Digora Optime PSP, Vistascan PSP and analogue intraoral radiographs significantly more voids were detected than with Accuitomo CBCT images ($0.00 < P < 0.02$) while there was no significant difference between the three digital intraoral systems.

Taking into account root level differences, the following comparisons were statistically different:

1. At 7 mm short of the apex, Accuitomo CBCT images were significantly less effective to detect voids compared with Vistascan PSP images ($P = 0.04$).

2. At 10 mm short of the apex, Accuitomo CBCT images were significantly less effective to detect voids compared with Vistascan PSP and Sigma CCD images ($P = 0.01$, $P = 0.01$ respectively).

3. At 13 mm short of the apex this was the same for Accuitomo CBCT images compared with Vistascan PSP, Sigma CCD and analogue intraoral radiographs ($P = 0.02$, $P = 0.01$, $P = 0.01$ respectively).

Table 4 Comparison of void detection among different imaging technique groups

A — 200 µm voids

IMAGING SYSTEM	ROOT LEVEL (mm) 1	4	7	10	13	all
1/2	NS	NS	NS	NS	NS	S
1/3	NS	NS	NS	NS	NS	NS
1/4	S	S	NS	S	NS	S
1/5	S	S	S	S	NS	S
2/3	NS	NS	NS	NS	NS	S
2/4	S	NS	NS	NS	NS	S
2/5	S	NS	S	S	NS	S
3/4	S	NS	NS	S	NS	S
3/5	S	NS	S	S	S	S
4/5	NS	NS	NS	NS	NS	NS

B — 300 µm voids

IMAGING SYSTEM	ROOT LEVEL (mm) 1	4	7	10	13	all
1/2	NS	NS	NS	NS	NS	NS
1/3	NS	NS	NS	NS	NS	NS
1/4	NS	NS	NS	S	S	S
1/5	NS	NS	NS	NS	NS	NS
2/3	NS	NS	NS	NS	NS	NS
2/4	NS	NS	NS	NS	NS	S
2/5	NS	NS	NS	NS	NS	NS
3/4	NS	NS	S	S	S	S
3/5	NS	NS	NS	NS	NS	S
4/5	NS	NS	NS	NS	S	NS

C — 350 µm voids

IMAGING SYSTEM	ROOT LEVEL (mm) 1	4	7	10	13	all
1/2	NS	NS	NS	NS	NS	NS
1/3	NS	NS	NS	NS	NS	NS
1/4	NS	NS	NS	NS	NS	NS
1/5	NS	NS	NS	NS	NS	NS
2/3	NS	NS	NS	NS	NS	NS
2/4	NS	NS	NS	NS	NS	NS
2/5	NS	NS	NS	NS	NS	NS
3/4	NS	NS	NS	NS	NS	NS
3/5	NS	NS	NS	NS	NS	NS
4/5	NS	NS	NS	NS	NS	NS

D — 500 µm voids

IMAGING SYSTEM	ROOT LEVEL (mm) 1	4	7	10	13	all
1/2	NS	NS	NS	NS	NS	NS
1/3	NS	NS	NS	NS	NS	NS
1/4	NS	NS	NS	NS	NS	NS
1/5	NS	NS	NS	NS	NS	NS
2/3	NS	NS	NS	NS	NS	NS
2/4	NS	NS	NS	NS	NS	NS
2/5	NS	NS	NS	NS	NS	NS
3/4	NS	NS	NS	NS	NS	NS
3/5	NS	NS	NS	NS	NS	NS
4/5	NS	NS	NS	NS	NS	NS

E — 800 µm voids

IMAGING SYSTEM	ROOT LEVEL (mm) 1	4	7	10	13	all
1/2	NS	NS	NS	NS	NS	NS
1/3	NS	NS	NS	NS	NS	NS
1/4	NS	NS	NS	NS	NS	NS
1/5	NS	NS	NS	NS	NS	NS
2/3	NS	NS	NS	NS	NS	NS
2/4	NS	NS	NS	NS	NS	NS
2/5	NS	NS	NS	NS	NS	NS
3/4	NS	NS	NS	NS	NS	NS
3/5	NS	NS	NS	NS	NS	NS
4/5	NS	NS	NS	NS	NS	NS

F — All void sizes

IMAGING SYSTEM	
1/2	S
1/3	NS
1/4	S
1/5	S
2/3	S
2/4	S
2/5	NS
3/4	S
3/5	S
4/5	NS
(1+2+3)/4	S
(1+2+3)/5	S

S, significant; NS, not significant; imaging system 1, Sigma CCD; 2, Digora Optime PSP; 3, Vistascan PSP; 4, Accuitomo CBCT; 5, E-speed film IO.

200 µm voids (Table 4A)

Generally, for 200 µm voids the respective percentages were as follows: 100.0%, 78.6%, 85.7%, 28.6% and 14.3%. Using Sigma CCD images, void detection percentages were significantly high than using Digora Optime PSP, Accuitomo CBCT and analogue intraoral

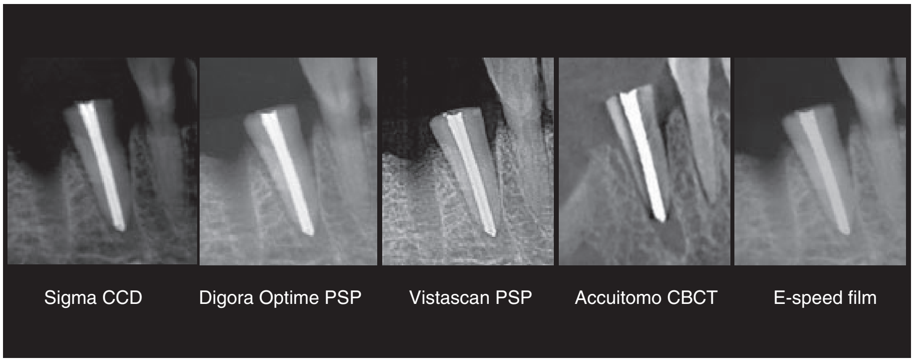

Figure 2 Radiographs of the same specimen (300 μm void) with different imaging techniques. The radiolucency surrounding the root filling (on Accuitomo CBCT images) is called a mach band and was not scored as a void.

Table 5 Comparison of void detection among different root level groups

	Void size(μm)						Void size(μm)				
Root level (mm)	200	300	350	500	800	Root level (mm)	200	300	350	500	800
(A) Imaging system 1						(B) Imaging system 2					
1/4	NS	NS	NS	NS	NS	1/4	NS	NS	NS	NS	NS
1/7	NS	NS	NS	NS	NS	1/7	NS	NS	NS	NS	NS
1/10	NS	NS	NS	NS	NS	1/10	NS	NS	NS	NS	NS
1/13	NS	NS	NS	NS	NS	1/13	NS	NS	NS	NS	NS
4/7	NS	NS	NS	NS	NS	4/7	NS	NS	NS	NS	NS
4/10	NS	NS	NS	NS	NS	4/10	NS	NS	NS	NS	NS
4/13	S	NS	NS	NS	NS	4/13	NS	NS	NS	NS	NS
7/10	NS	NS	NS	NS	NS	7/10	NS	NS	NS	NS	NS
7/13	NS	NS	NS	NS	NS	7/13	NS	NS	S	NS	NS
10/13	S	NS	NS	NS	NS	10/13	NS	NS	NS	NS	NS
(C) Imaging system 3						(D) Imaging system 4					
1/4	NS	NS	NS	NS	NS	1/4	NS	NS	NS	NS	NS
1/7	NS	NS	NS	NS	NS	1/7	NS	NS	NS	NS	NS
1/10	NS	NS	NS	NS	NS	1/10	NS	NS	NS	NS	NS
1/13	NS	NS	NS	NS	NS	1/13	NS	NS	NS	NS	NS
4/7	NS	NS	NS	NS	NS	4/7	NS	NS	NS	NS	NS
4/10	NS	NS	NS	NS	NS	4/10	NS	NS	NS	NS	NS
4/13	NS	NS	NS	NS	NS	4/13	NS	NS	NS	NS	NS
7/10	NS	NS	NS	NS	NS	7/10	NS	NS	NS	NS	NS
7/13	NS	NS	NS	NS	NS	7/13	NS	NS	NS	NS	NS
10/13	NS	NS	NS	NS	NS	10/13	NS	NS	NS	NS	NS
(E) Imaging system 5											
1/4	NS	NS	NS	NS	NS						
1/7	NS	NS	NS	NS	NS						
1/10	NS	NS	NS	NS	NS						
1/13	NS	NS	NS	NS	NS						
4/7	NS	NS	NS	NS	NS						
4/10	NS	NS	NS	NS	NS						
4/13	NS	NS	NS	NS	NS						
7/10	NS	NS	NS	NS	NS						
7/13	NS	NS	NS	NS	NS						
10/13	NS	NS	NS	NS	NS						

S, significant; NS, not significant; imaging system 1, Sigma CCD; 2, Digora Optime PSP; 3, Vistascan PSP; 4, Accuitomo CBCT; 5, E-speed film IO.

images (all $P = 0.00$). The same was true for Vistascan PSP images compared with Digora Optime PSP ($P = 0.005$), Accuitomo CBCT ($P = 0.00$) and analogue intraoral images ($P = 0.00$). Void detection percentages were significantly higher when using Digora Optime PSP images compared with Accuitomo PSP and analogue intraoral images (both $P = 0.00$) and significantly lower when using Digora Optime PSP images compared with Vistascan PSP ($P = 0.005$) and Sigma CCD images ($P = 0.00$).

Taking into account root level differences, the following comparisons were statistically different:

1. At 1 mm short of the apex, the void detection percentages generated when using Sigma CCD, Digora Optime PSP and Vistascan PSP were significantly higher compared with the void detection percentages generated when using as well Accuitomo CBCT images as analogue intraoral radiographs ($0.05 > P > 0.01$).

2. At 4 mm short of the apex, when using Sigma CCD images, void detection percentages were significantly higher than when using Accuitomo CBCT images and analogue intraoral radiographs ($P < 0.01$).

3. At 7 mm short of the apex, when using Sigma CCD, Digora Optime PSP and Vistascan PSP images, void detection percentages were significantly higher than when using analogue intraoral radiographs ($0.04 > P > 0.01$).

4. At 10 mm short of the apex, when using Sigma CCD, Digora Optime PSP and Vistascan PSP, void detection percentages were significantly higher than when using analogue intraoral radiographs ($P < 0.01$). When using Sigma CCD and Vistascan PSP images, void detection percentages were significantly higher than when using Accuitomo CBCT images ($P = 0.02$, $P = 0.01$ respectively).

5. At 13 mm short of the apex, when using Vistascan PSP images, void detection percentages were higher than when using analogue intraoral radiographs ($P = 0.04$).

Comparison of void detection among different root level groups

'Root level' was not a factor playing a determining role in void detection. This can be concluded from the inconsistent results below (Tables 1 and 5A–E).

Sigma CCD (Table 5A)

Only in the 200 μm void group at 13 mm short of the apex, detection rates were significantly less compared with 4 and 10 mm short of the apex ($P < 0.05$).

Digora Optime PSP (Table 5B)

Only in the 350 μm void group at 7 mm short of the apex, detection rates were significantly less compared with 13 mm short of the apex ($P = 0.01$).

Vistascan PSP, Accuitomo CBCT and analogue intraoral radiographs (Table 5C–E)

There were no significant differences at all among the different root levels ($1.00 > P > 0.50$).

Discussion

Voids in root fillings can, theoretically, compromise the outcome of root canal treatment. Clinically, voids in root fillings are difficult to detect. The post-treatment radiograph is the benchmark for the quality of the root filling and is the only way to determine the density of the filling and the presence of voids. It is unclear to what extend void size, imaging technique and position in the root canal influence the detectability of voids in root fillings.

In this study, the root canal preparation (800 μm) was large compared with most clinical situations. This preparation size was chosen according to the thickest wire size and also to allow perfect standardization (eliminating the factor 'root canal diversity') of the irrigation and filling procedures. By creating a large root canal diameter, accidental voids in the root canal filling were avoided. The 0.0% void detection rate on the images of the entirely filled canals, suggests the absence of relevant accidental voids that could interfere with the standardized void detection in the experimental group.

A human skull with soft tissue simulator and human teeth were chosen to mimic the clinical situation as close as possible. X-ray tube settings were, again, chosen according to the standard clinical protocol.

Observers were trained through a stringent calibration procedure. The informative and panel discussion session, as parts of this procedure, decreased the interobserver variety. This was confirmed statistically with an overall good correlation resulting. The observers were well aware of the 'mach band effect' (as seen on the CBCT image in Fig. 2) and were encouraged to score only voids within the root fillings in an attempt to rule out artefactual false positive results.

The acquired images were presented to the observers in random order, in the same light obscured room, under the same magnification (×2) to avoid favouring one or other of the 5 imaging systems. They were asked whether they could determine a void and at what level(s) in the root canal they could see a void. All these 'yes/no' scores were converted to '1/0' values and immediately transferred to an Excel sheet (Microsoft, Redmond, WA, USA). A biomedical statistician performed analysis on these data (generalized mixed model, ANOVA analysis, Tukey–Kramer correction for simultaneous hypotheses testing, significance level 0.05).

Five different levels of the root canal were chosen to score void presence or absence. This was done because the anatomical cone shape of the roots and root canals, the thickness of the filling material and the fact that dentine may overlap more in the coronal region could hide voids partially or completely. It was decided to keep the same diameter size of the void at all root levels. Therefore the voids were, theoretically, more difficult to detect in the coronal sections and easier in the apical. This may be clinically helpful following the finding that the radiographic presence of voids in the apical and middle thirds of root fillings was associated with significantly lower mean survival time than the presence of voids found in the coronal third or no voids at all (Cheung 2002).

'Root level', however, was not a consistent significant determining factor in this study, but rather a confusing factor. This means that there was no evidence that voids could be detected more predictably at certain root levels. Although in the middle and coronal third there should be more superimposed dentine and filling thickness, there was no overall significant difference in void detection rate between voids located in the apical compared with the coronal region. This could be explained by the very large apical preparation and further work could be directed at more moderate apical instrumentation diameters.

'Void size' was a main determining factor as all voids larger than 300 μm could be detected (although not at every root level) with every imaging system. This corroborates with other studies showing that diagnostic performance of digital intraoral images and analogue intraoral radiographs for simulated void detection in root fillings was not significantly different (Kositbowornchai *et al.* 2006). This means that smaller voids (≤300 μm) are of special interest when comparing different imaging systems. These voids are of particular interest since in the clinical setting, these void sizes are more likely to occur, even when high quality clinical care is provided.

In this study 'imaging technique' was a main determining factor and when the Sigma CCD system was used every void was detected, irrespective of void size and root level and was the best system in this respect. Although the other digital intraoral systems were also accurate, detection of the smallest voids was significantly less accurate with these systems. In general, analogue intraoral radiographs and Accuitomo CBCT images were ineffective for the detection of small voids. When comparing the spatial resolution of the intraoral systems (Sigma CCD 11 lp mm^{-1}, Digora Optime PSP 8 lp mm^{-1}, Vistascan 20 lp mm^{-1}, E-speed film ≥20 lp mm^{-1}), there was no unequivocal increase in void detection rate for images taken with higher spatial resolution systems. This corroborates with the work of Wenzel *et al.* (2007), who came to the same conclusion for caries detection.

Although practitioners, generally, still prefer analogue intraoral radiographs for endodontic procedures, this study shows that with the more contemporary digital intraoral techniques, small standardized voids can be detected more easily with a digital intraoral imaging system. The 3D advantage of CBCT does not seem to offer advantages for small void detection. This is possibly caused by the lower resolution features of the CBCT system used in this study and by artefacts caused by the radiopaque filling material. Further research should be undertaken with newer CBCT devices and updated digital intraoral systems, preferably with more moderate apical preparation diameters to fully understand the void detection potential features of different imaging techniques at different void sizes and root level combinations. Only then, firm clinically relevant conclusions can be drawn on the value of different imaging systems for technical quality control of root fillings.

Conclusions

For voids ≥350 μm, all systems allowed detection by the examiners. For voids <350 μm, digital intraoral techniques had similar void detection rates, which were better than analogue intraoral radiographs and CBCT images. All digital intraoral radiography systems provided useful information for void detection and these may be preferred to analogue intraoral radiographs and CBCT images. Moreover, Sigma CCD images revealed all voids. 3D CBCT data sets of the current resolution do not seem to offer additional information regarding the detection of voids.

Acknowledgements

The authors greatly want to acknowledge Orasan Alin, Daniel Leucuta, Limin Li, Xin Liang, Elisabeth

Huntjens, Voichita Sabadus, Cristina Alexa and Ioana Chifor for their contribution to this research study.

A special thanks to Wim Coucke for the biostatistical analysis.

References

Cheung GS (2002) Survival of first-time nonsurgical root canal treatment performed in a dental teaching hospital. *Oral Surgery Oral Medicine Oral Pathology Oral Radiology and Endodontics* **93**, 596–604.

Dummer PM, Lyle L, Rawle J, Kennedy JK (1994) A laboratory study of root fillings in teeth obturated by lateral condensation of gutta-percha or Thermafil obturators. *International Endodontic Journal* **27**, 32–8.

Estrela C, Bueno MR, Leles CR, Azevedo B, Azevedo JR (2008) Accuracy of cone beam computed tomography and panoramic and periapical radiography for detection of apical periodontitis. *Journal of Endodontics* **34**, 273–9.

Greenhill JD, Pashley DH (1981) The effects of desensitizing agents on the hydraulic conductance of human dentin *in vitro*. *Journal of Dental Research* **60**, 686–98.

Guerrero ME, Jacobs R, Loubele M, Schutyser F, Suetens P, van Steenberghe D (2006) State-of-the-art on cone beam CT imaging for preoperative planning of implant placement. *Clinical Oral Investigations* **10**, 1–7.

Kersten HW, Fransman R, Thoden van Velzen SK (1986) Thermomechanical compaction of gutta-percha. II. A comparison with lateral condensation in curved root canals. *International Endodontic Journal* **19**, 134–40.

Kositbowornchai D, Hanwachirapong D, Somsopon R, Pirmsinthavee S, Sooksuntisakoonchai N (2006) *Ex vivo* comparison of digital images with conventional radiographs for detection of simulated voids in root canal filling material. *International Endodontic Journal* **39**, 287–94.

Lane EJ, Proto AV, Phillips TW (1976) Mach bands and density perception. *Radiology* **121**, 9–17.

Lavelle CL (1999) The role of direct intraoral sensors in the provision of endodontic services. *Endodontics and Dental Traumatology* **15**, 1–5.

Li G, Sanderink GC, Welander U, McDavid WD, Nasstrom K (2004) Evaluation of endodontic files in digital radiographs before and after employing three image processing algorithms. *Dentomaxillofacial Radiology* **33**, 6–11.

Lin LM, Skribner JE, Gaengler P (1992) Factors associated with endodontic treatment failures. *Journal of Endodontics* **18**, 625–7.

Lofthag-Hansen S, Huumonen S, Gröndahl K, Gröndahl HG (2007) Limited cone-beam CT and intraoral radiography for the diagnosis of periapical pathology. *Oral Surgery Oral Medicine Oral Pathology Oral Radiology and Endodontics* **103**, 114–9.

Low KM, Dula K, Bürgin W, von Arx T (2008) Comparison of periapical radiography and limited cone-beam tomography in posterior maxillary teeth referred for apical surgery. *Journal of Endodontics* **34**, 557–62.

Miles DA, Van Dis ML (1993) Imaging using solid-state detectors. *Dental Clinics of North America* **37**, 531–40.

Peters LB, Wesselink PR, Moorer WR (1995) The fate and the role of bacteria left in root dentinal tubules. *International Endodontic Journal* **28**, 95–9.

Pitt Ford TR (1983) Relation between seal of root fillings and tissue response. *Oral Surgery Oral Medicine Oral Pathology* **55**, 291–4.

Sogur E, Baksi BG, Grondahl HG (2007) Imaging of root canal fillings: a comparison of subjective image quality between limited cone-beam CT, storage phosphor and film radiography. *International Endodontic Journal* **40**, 179–85.

Stavropoulos A, Wenzel A (2006) Accuracy of cone beam dental CT, intraoral digital and conventional film radiography for the detection of periapical lesions. An ex vivo study in pig jaws. *Clinical Oral Investigations* **11**, 101–6.

Van den Berg HR, Ten Seldam CA, Van der Gulik PS (1993) Compressible laminar flow in a capillary. *Journal of Fluid Mechanics* **246**, 1–20.

Wallace JA, Nair MK, Abomr D, Colaco MF, Kapa SF (2001) A comparative evaluation of the diagnostic efficacy of film and digital sensors for detection of simulated periapical lesions. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology and Endodontics* **92**, 93–7.

Wenzel A, Haiter-Neto F, Gotfredsen E (2007) Influence of spatial resolution and bit depth on detection of small caries lesions with digital receptors. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology and Endodontics* **103**, 418–22.

White DR (1977) Phantom materials for photons and electrons. *The Hospital Physicists' Association, Radiotherapy Topic Group. Scientific Report Series* **20**, 1–30.

Wu MK, De Gee AJ, Wesselink PR, Moorer WR (1993) Fluid transport and bacterial penetration along root canal fillings. *International Endodontic Journal* **26**, 203–8.

Wu MK, Dummer PM, Wesselink PR (2006) Consequences of and strategies to deal with residual post-treatment root canal infection. *International Endodontic Journal* **39**, 343–56.