Clin Oral Invest (2011) 15:537–549
DOI 10.1007/s00784-010-0416-8

ORIGINAL ARTICLE

A comprehensive in vitro study of image accuracy and quality for periodontal diagnosis. PART 1: The influence of X-ray generator on periodontal measurements using conventional and digital receptors

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Received: 20 August 2009 / Accepted: 14 April 2010 / Published online: 5 May 2010

Abstract The aim of this study was the determination of image accuracy and quality for periodontal diagnosis using various X-ray generators with conventional and digital radiographs. Thirty-one in vitro periodontal defects were evaluated on intraoral conventional (E-, F/E-speed) and digital images (three indirect, two direct sensors). Standardised radiographs were made with an alternating current (AC), a high-frequency (HF) and a direct current (DC) X-ray unit at rising exposure times (20–160 ms with 20-ms interval) with a constant kV of 70. Three observers assessed bone levels for comparison to the gold standard. Lamina dura, contrast, trabecularisation, crater and furcation involvements were evaluated. Irrespective X-ray generator-type, measurement deviations increased at higher exposure times for solid-state, but decreased for photostimulable storage phosphor (PSP) systems. Accuracy for HF or DC was significantly higher than AC ($p<0.0001$), especially at low exposure times. At 0.5- to 1-mm clinical deviation, 27–53% and 32–55% dose savings were demonstrated when using HF or DC generators compared to AC, but only for PSP. No savings were found for solid-state sensors, indicating their higher sensitivity. The use of digital sensors compared to film allowed 15–90% dose savings using the AC tube, whilst solid-state sensors allowed approximately 50% savings compared to PSP, depending on tube type and threshold level.. Accuracy of periodontal diagnosis increases when using HF or DC generators and/or digital receptors with adequate diagnostic information at lower exposure times.

Keywords Tube potential · Exposure time · Intraoral radiography · Digital · Image quality · Periodontal bone height

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Introduction

The rapid evolution towards digital imaging has brought several advantages in patient treatment and disease diagnosis. Digitalisation has reduced the required radiation dose for dental imaging [1–5], allowed the use of image enhancement [6–11] and brought an overall easier and faster workflow [10, 12]. Furthermore, the amount of quality assurance steps has been downsized due to the elimination of the many processing steps of conventional film development, with the final diagnostic quality of digital images now mostly depending on a specific sensor's sensitivity profile and resolution and the X-ray generator's exposure settings. Due to the fast technology turnover, many studies have investigated the constant improvement of film or digital sensor sensitivity and resolution. Reports have demonstrated dose savings of 50% when using E/F-speed films compared to D-speed types [13] and even further savings when using digital sensors [1, 2]. However, the X-ray generator and its specific settings have often not been explored despite their direct impact on radiographic contrast and image density [14].

International recommendations on mA (tube current or beam intensity) and kV (tube voltage or penetration level) ranges—usually fixed on dental X-ray units—have been published [15], but actual exposure times (or mAs) for intraoral radiographs still need to be balanced towards receptor- and X-ray generator type. Traditional X-ray units based on alternating current (AC) delivered sinusoidal potentials between a positive and negative voltage peak, only generating X-rays in a fraction of the time (positive wave-peak), whilst the rest of the wave only contributed to scatter radiation. Most AC units now have rectified this negative backflow of electrons, but more modern high-frequency (HF) units oscillate between higher voltages and therefore produce more useful X-rays during one cycle and less unnecessary low-energy photons [16]. Although the latest HF or multi-pulse waves resemble those of constant potential generators, HF units are marked by a small preheating time: kV variation (or ripple) decreases at rising exposure times. Constant potential generators (direct current or DC) produce a harder beam with smaller ripple and no preheating. For many years now, the impact of these different waveforms have been investigated using experimental phantom tests and indicated possible skin dose savings by maintaining subject contrast. Unfortunately, up to now, no studies have reported the clinical impact on diagnostic image quality. Especially in combination with sensitive digital sensors, a more accurate and predictable X-ray output obtained by DC generation may allow further dose savings [15]. Surprisingly, most studies on digital imaging have not considered X-ray generator type in the determination of exposure range. Direct solid-state sensors (complementary metal–oxide semiconductors (CMOS) and charged coupled device (CCD)) and indirect imaging plates (photostimulable storage phosphor or PSP) have namely different sensitometric properties which may be influenced by the X-ray generator type.

For general dental diagnosis, Borg et al. [19] compared the subjective image quality ratings (visibility of important structures) for varying exposure times using several digital systems and a DC tube. They found PSP systems to have a wider useful exposure range and CCD the narrowest. In a similar research setup, Bhaskaran et al. [20] and Berkhout et al. [21] found comparable results, although a HF generator was used. Similarly, for periodontal diagnosis, no studies could be found investigating different X-ray generators, but in addition, most studies did not explore exposure ranges [8, 9, 11, 22–26]. Pecoraro et al. [26] investigated observer reliability in assessing periodontal bone height using conventional E-speed film and a digital CMOS sensor and found no significant difference when using the digital system. However, the X-ray generator used was of the AC type and, in addition, the exposure range was halved for the digital system without investigating other exposure times. As a matter of fact, the added value from (digital) radiography for periodontal diagnosis has often been questioned because research in digital imaging is lacking [27–29]. Only one study explored a range of radiographic exposure times in the detection of periodontal bone loss using two digital systems and a DC tube, but high exposure times—comparable to film—were used [6].

Therefore, the overall aim of this study was to investigate the effect of X-ray tube generator on image accuracy and quality for the assessment of periodontal bone lesions using conventional and digital imaging receptors at a range of increasing exposure times.

Materials and methods

Thirty-one periodontal bone defects of two adult human skulls, a cadaver head and a dry skull, were evaluated using intraoral conventional and digital radiography. The upper and lower jaws of the cadaver head were fixed with 10% formalin and functioned as a clinical subject. The cadavers were obtained with permission and ethical approval from the Department of Anatomy at the Catholic University of Leuven, Belgium. The adult human dry skull was covered with a soft tissue substitute, Mix D, and used as a simulation [30]. For the intraoral protocol, the paralleling technique was applied in a standardised exposure setup. A film holding system (XCP, RINN Corporation, Elgin, IL, USA) was used and standardised repositioning and stabilisation was guaranteed by an individually adapted stent material, serving as a rigid occlusal key during exposure. These waxed imprints of the anterior, premolar and molar regions were made on the bite blocks of the radiographic aiming device (see Fig. 1a).

Intraoral X-ray units

To investigate the influence of X-ray generation, three X-ray generator types corresponding to AC (IRIX 70, Trophy Radiologie, Marne-La-Vallée, France), HF (Prostyle Intra, Planmeca Oy, Helsinki, Finland) and DC (Minray, Soredex, Tuusula, Finland) generators were used. Exposure settings were 70 kVp and 7 mA (Minray) or 8 mA (IRIX 70, Prostyle Intra). The different mA settings were recalculated for the analysis by using the product with exposure time (mAs). The exposure times used for conventional film and PSP were 0.020, 0.040, 0.060, 0.080, 0.120 and 0.160 s. For CCD, however, the used range was limited to 0.020 or 0.040, 0.060 and 0.080 s. A mechanically interlocking rectangular (4×3 cm) collimator (Universal Collimator,

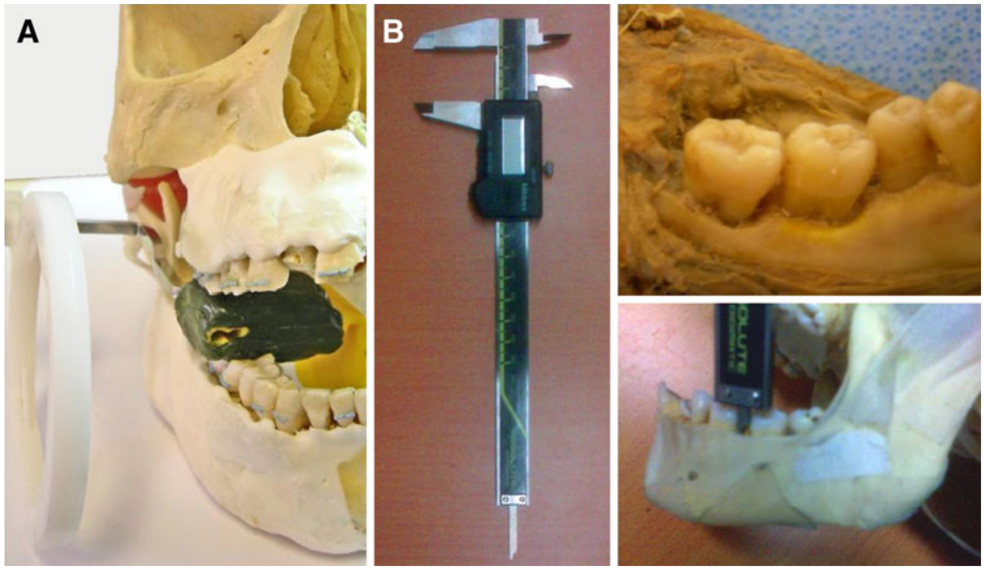

Fig. 1 **a** Standardized intraoral radiographic exposure setup: aiming and positioning device with occlusal keys (*green stent*, notice the soft tissue simulation on the dry skull). **b** Digital calliper with inside and outside measurements and depth blade. For the cadaver jaws, measurements were done after flapping. The depth blade allowed measuring infrabony defects to the base of the crater

RINN Corporation) was used for the AC and HF units for comparison to the DC unit, equipped with an integrated 3× 4-cm beam collimation. The focal film distance was (set to) 30 cm for all tubes.

Imaging modalities

For the radiographic assessments, peri-apical radiographs were made with conventional film, indirect digital and direct digital systems using the standardised setup. The conventional films used in this study were Agfa Dentus M2 Comfort E-speed film (Heraeus Kulzer GmbH, Dormagen, Germany) and Kodak Insight F/E-speed film (Carestream Health, Rochester, NY, USA). The indirect digital PSP systems were Digora Optime (Soredex), Vistascan (12 bit) and Vistascan Perio (16 bit; Dürr Dental GmbH, Bietigheim-Bissingen, Germany). For the Vistascan 12 bit, both original and images with a dedicated periodontal filter were included for analysis. The direct digital CCD sensors were Sigma (Instrumentarium Dental, Tuusula, Finland) and VistaRay (Dürr Dental GmbH). Two examples of the radiographic setup are given in Figs. 2 and 3: The three X-ray generators are combined with a PSP (Fig. 2) and a CCD (Fig. 3) system whilst exposure time is increased.

Radiographic assessments

The radiographic assessments consisted of objective measurements on one hand and subjective evaluations on the other hand. Images were viewed by three observers (all dentists specialised in oral imaging) in a darkened room on three standardised notebooks with 17-in. TFT-based LCD monitors (contrast ratio 750:1) having anti-reflective layers, same screen resolution (1,440×900 pixels) and contrast and brightness levels. The intraoral peri-apical images from all possible X-ray tube, image receptor and exposure time combinations were exported in Tagged Image File Format (TIFF) and displayed in a random order with the Emago Advanced, V.3.5.2. software (Oral Diagnostic Systems, Amsterdam, The Netherlands) at true size (pixel size × number of pixels, ratio 1:1). Image processing, including zoom functions, was not allowed for the digital observer assessments. The conventional films were processed with an automatic film processor (XR24 Nova, Dürr Dental) with Dürr Chemistry (Röntgen Spezial-Set fur Dürr Automat XR24). The films were viewed in a darkened room using a 6×12-in. countertop illuminator (Universal Viewer, Dentsply International, York, PA, USA) with magnifier and film mounts to cover surrounding light.

For the objective measurements, 31 sites were selected, including naturally occurring linear defects, three-dimensional craters and furcation involvements, to measure periodontal bone levels. The observers were asked to measure the distance from the cemento-enamel junction to the alveolar bone using the linear measurement tool of the Emago Advanced software or for the conventional films using a digital sliding calliper (Mitutoyo, Andover, UK) both with an accuracy to the nearest 0.1 mm. Physical measurements of the skulls were considered as the gold standards for further accuracy assessment of all imaging combinations. For the cadaver jaws, the gold standard was obtained after image acquisition by flap surgery to allow physical measurements using a digital sliding calliper (Mitutoyo) with accuracy to the nearest 0.01 mm. For the dry skull, however, gold standards were obtained prior to adding soft tissue substitute and image acquisition. Mesial, central and distal bone levels and bone crater depths on the oral and vestibular sides of each selected tooth were measured by two observers using the inside measurement arms of the calliper and averaged. For infrabony defects

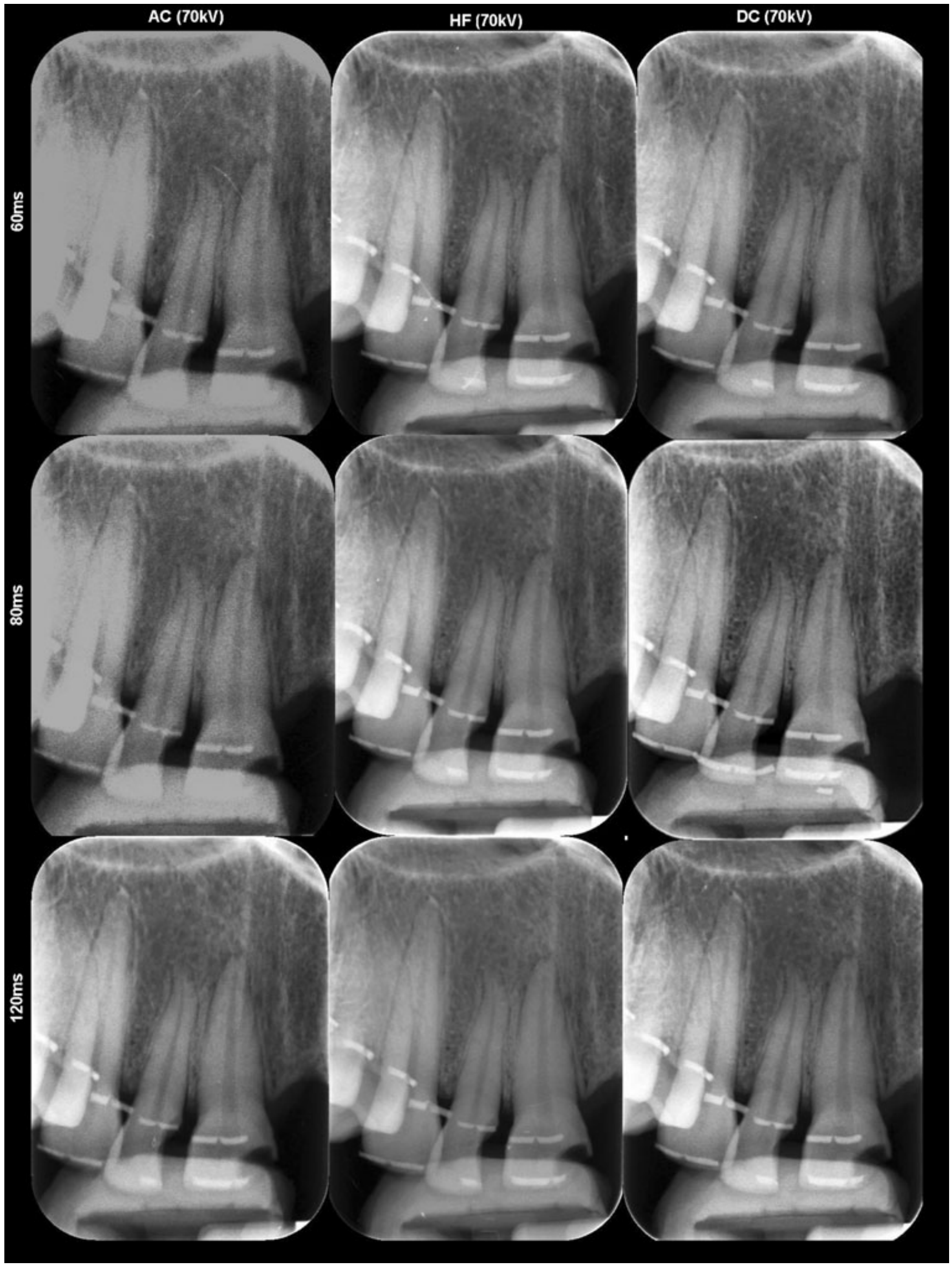

Fig. 2 PSP radiographs (front region) of the standardized dry skull with three X-ray generator types at rising exposure times. Notice the increase in radiographic contrast from left to right (AC to HF to DC), but mostly at low exposure times. From the top down (60 to 80 to 120 ms), this difference is less apparent except for the AC tube

containing several walls, the depth blade was used allowing measurements until the base of the defect (see Fig. 1b). Because of dehydration of the dry skull, the faded CEJ could not be used as a reference point as in the formalin-fixed cadaver jaws. Therefore, radio-opaque gutta-percha fragments with a small central indentation were glued onto the respective teeth to serve as standardised fiducials.

For the subjective evaluations, important periodontal diagnostic criteria were analysed by the three observers. The delineation of lamina dura, crater visibility, furcation involvement visibility, depiction of trabecular bone and radiographic contrast was evaluated on all images. An ordinal scale was assigned to these variables, ranging from 0 to 3 (1=bad, 2=medium, 3=good), with 0 as a score when it was not possible for an observer to evaluate the criterion properly.

Dose measurements

Using a Barracuda multimeter (RTI Electronics AB, Mölndal, Sweden) with a solid-state dose detector (R100 dose probe), the kV, time, pulses, dose, dose rate, dose per pulse, half value layer and filtration were measured for the AC, HF and DC units within a range of 0 to 200 ms. The

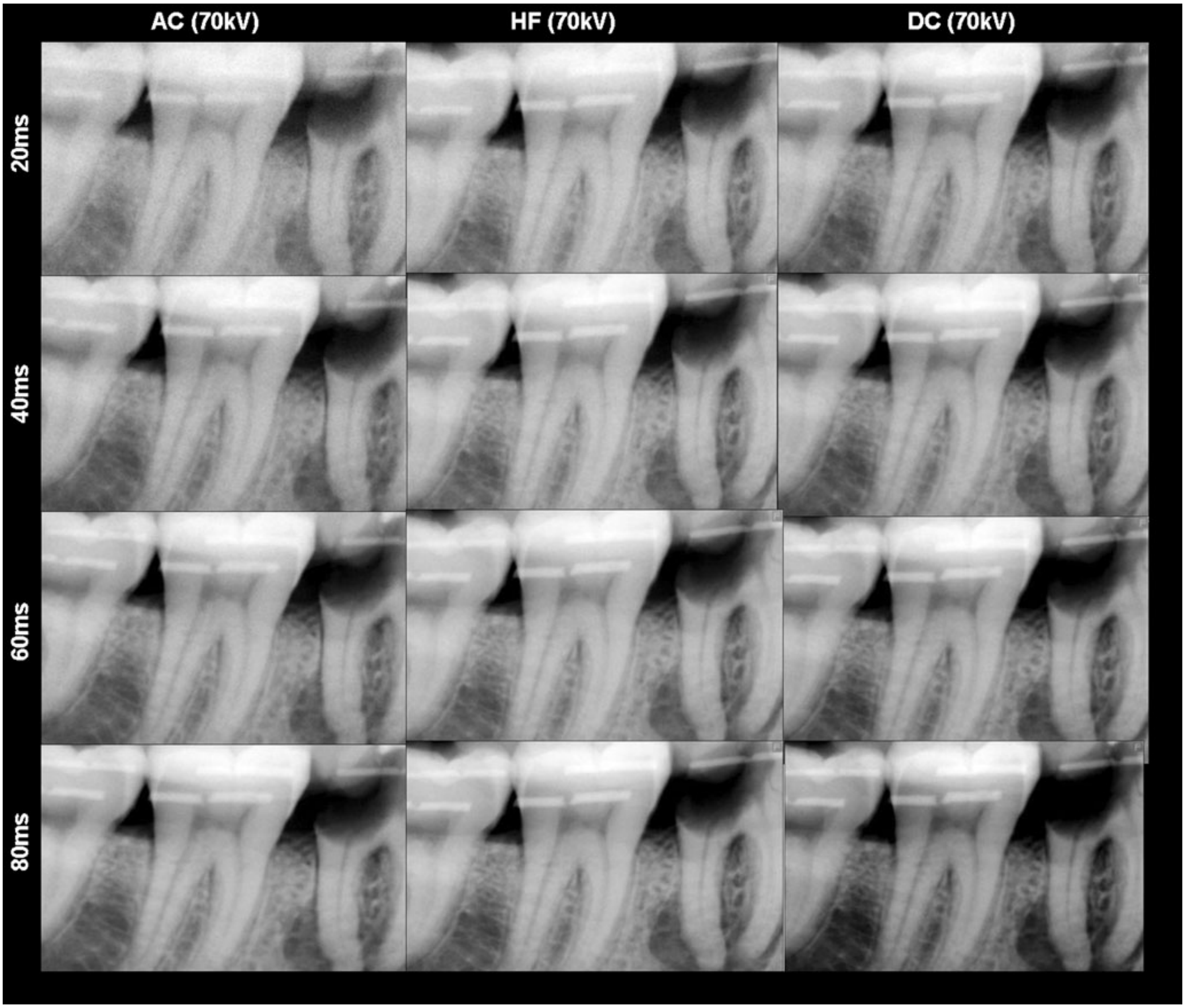

Fig. 3 CCD radiographs (molar region) of the standardized dry skull with the three X-ray generator types at rising exposure times. Notice the change in radiographic contrast from left to right (AC to HF to DC) especially at low exposure times. From the top down (rising exposure), this change can also be noticed, and at high exposure times, blooming effects (darkening of the alveolar crest) become apparent especially when using the DC tube

probe was positioned at the same source distance for the three tube types. Accuracy of the multimeter was tested, indicating a range within 3% inaccuracy for entrance dose and <1% for kV measurements.

Statistical methodology

All analyses have been performed using SAS software, version 9.2, of the SAS System for Windows [31].

Table 1 gives an overview of the number of measurements per combination of X-ray tube image receptor (group) and exposure time. In the analyses, seven groups are distinguished defined by tube and image receptor combination.

Accuracy

The accuracy of measurements has been defined as the absolute distance from the gold standard (GS). In some cases, radiographic image quality was too low for the observer to obtain an actual measurement. In, respectively, 302, 5, 29 and 2143 (86.4%) cases, none, only one, only two and all three observers made an actual measurement. Ignoring this rather large set of cases would substantially bias the evaluation of the accuracy. In case no bone level measurement was possible due to lack of image quality, the measurement accuracy was considered to be right-censored at an arbitrarily value of 6, a value which exceeds the lowest observed measure-

Table 1 Number of measurements presented by exposure time and group

Group	Exposure time							
Frequency	0<ms≤20	20<ms≤40	40<ms≤60	60<ms≤80	80<ms≤100	100<ms≤140	ms > 140	Total
Film, AC (kV=70)	0	58	58	58	58	58	58	348
PSP, AC (kV=70)	0	62	62	62	62	62	62	372
PSP, HF (kV=70)	0	62	62	62	62	62	62	372
PSP, DC (kV=70)	124	124	124	124	0	124	124	744
CCD, AC (kV=70)	0	27	27	116	116	89	0	375
CCD, HF (kV=70)	0	27	27	27	27	0	0	108
CCD, DC (kV=70)	40	40	40	40	0	0	0	160
Total	164	400	400	489	325	395	306	2,479

A total of 2,479 bone level measurements were done by each observer. For example, measurements for the 31 bone defects are obtained with four different PSP systems/configurations at exposure time ≤20 ms, resulting in 124 measurements made by each of the three observers. Note that some landmarks can be missing on radiographs with smaller receptor size, for instance CCD vs. PSP size. The exposure time is recalculated from mAs, if mA were equal to 7

ment accuracy (the lower the accuracy, the higher the absolute distance from the GS). As a result, the statistical analysis of accuracy was cast into a survival analysis framework. The accuracy has been averaged over the three observers. In the 34 cases with a discrepancy between the observers in assigning an actual value, the mean accuracy was also considered right-censored.

Comparisons were made between groups separately within intervals of exposure level (≤20 ms, 20–40 ms). Kaplan–Meier estimates were used to visualise the cumulative distribution function of the distance from the gold standard. The hazard for an accurate measurement was compared between the groups using a Cox model. Since each combination of bone defect and group was measured repeatedly (by possible multiple products and multiple exposure levels), this clustered structure was accounted for using the COVS option in the PROC PHREG procedure. For each combination of bone defect and group, a Spearman correlation was calculated to quantify the relation between the exposure level and accuracy. A Wilcoxon signed-rank test was then used to verify if the distributions of this set of correlations differed from zero.

Subjective measurements

For illustrative purposes only, the mean of the ordinal scores (giving a zero value in case the quality was too low to make an assessment) has been plotted for each group separately as a function of the exposure time. Note that for each of the skulls, only one measurement was present with each device combination (receptor tube) at a specific exposure level. Interest was in the relation between exposure level and rating (ignoring the device) and the differences between the tubes (ignoring exposure level and image receptor). A proportional odds model was used to model the ratings (0–1–2–3) as a function of exposure level and tube, respectively. Generalised estimating equations were used to take into account the aforementioned clustered structure (using PROC GENMOD). These models have been fitted for each observer separately. In all analyses, p values smaller than 0.05 were considered to be significant.

Results

Measurement accuracy

Figure 4 presents the cumulative distribution function (based on Kaplan–Meier estimates) of the absolute distance from the gold standard. This function gives the percentage of measurements (*Y*-axis) falling within a specific distance (*X*-axis) from the gold standard. Hence, the faster the curve increases, the higher the accuracy. The groups are compared within intervals of exposure range (≤20 ms, 20 ms< ms≤40 ms,…, ms > 140 ms). Table 2 summarises some relevant results from the Cox regression models comparing the accuracy between various groups within ranges of exposure level.

When considering the X-ray generator type as a first variable, a lower accuracy was found for AC compared to HF or DC units (p<0.0001) at low exposure times (ms≤ 80 ms), although only for PSP sensors. For the HF vs. DC unit, a significant difference was only found at very short exposure times (20<ms≤40) for PSP (p<0.0001), but again not for solid-state sensors.

When considering the image receptor as a second variable, differences in accuracy between PSP and CCD are especially seen when using the AC tube type. At shorter exposure times (ms≤80), measurements using direct sensors were more accurate than PSP, but this changed for

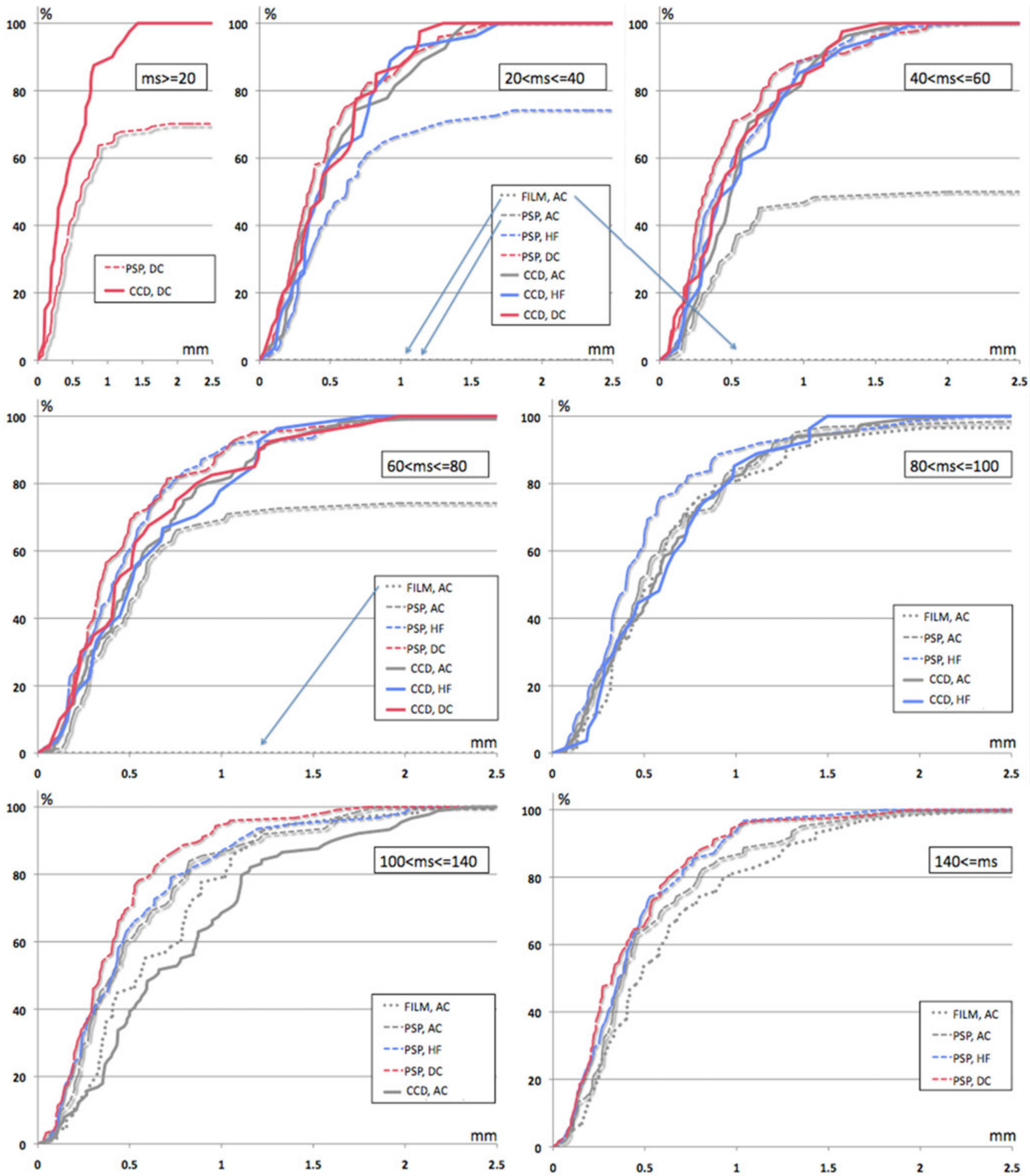

Fig. 4 Cumulative distribution function (based on Kaplan–Meier estimates) of the absolute distance from the gold standard. This function gives the percentage of measurements (*Y*-axis) falling within a specific distance (*X*-axis) from the gold standard. Hence, the faster the curve increases, the higher the accuracy. The graphs are presented at rising exposure intervals: ms≥20, 20<ms≤40,…, 140≤ms

higher exposure times (ms>100). On the other hand, for both HF and DC units, only at very small exposure times (respectively, ms≤40 and ms≤20) were significant differences found (respectively, $p<0.01$ and $p<0.001$). This indicated greater sensitivity of CCD receptors. In comparison to conventional film (only considered using AC), digital sensors produce more accurate measurements at low exposure times, except for PSP at ms≤40.

Table 2 Relevant results from the Cox regression models comparing the accuracy between various groups within ranges of exposure level

Group		Variable	Exposure time (at mA=7)						
			20≤ms	20<ms≤40	40<ms≤60	60<ms≤80	80<ms≤100	100<ms≤140	ms>140
Receptor type	PSP	AC vs. HF	x	*p*< *0.0001*	*p*< *0.0001*	*p*< *0.0001*	*p*>0.05	*p*>0.05	*p*>0.05
		AC vs. DC	x	*p*< *0.0001*	*p*< *0.0001*	*p*< *0.0001*	*p*>0.05	*p*>0.05	*p*>0.05
		HF vs. DC	x	*p*< *0.0001*	*p*>0.05	*p*>0.05	*p*>0.05	*p*>0.05	*p*>0.05
	CCD	AC vs. HF	x	*p*>0.05	*p*>0.05	*p*>0.05	x	x	x
		AC vs. DC	x	*p*>0.05	*p*>0.05	*p*>0.05	x	x	x
		HF vs. DC	x	*p*>0.05	*p*>0.05	*p*>0.05	x	x	x
Tube type	AC	Film vs. PSP	x	*p*>0.05	*p*< *0.0001*	*p*< *0.0001*	*p*>0.05	*p*>0.05	*p*>0.05
		Film vs. CCD	x	*p*< *0.0001*	*p*< *0.0001*	*p*< *0.0001*	*p*>0.05	*p*>0.05	x
		PSP vs. CCD	x	*p*< *0.0001*	*p*< *0.0001*	*p*< *0.0001*	*p*>0.05	*p*< *0.01**	x
	HF	PSP vs. CCD	x	*p*< *0.01*	*p*>0.05	*p*>0.05	*p*>0.05	x	x
	DC	PSP vs. CCD	*p*<0.001	*p*>0.05	*p*>0.05	*p*>0.05	x	x	x

The significant differences in italics indicate a greater accuracy for the second group vs. the first except for the significant difference marked by (*) which demonstrates greater accuracy for the first one. The [x] represents missing combinations, namely due to the lower exposure interval chosen for CCD receptors or due to mAs recalculation of the different tubes

Figure 5 is a graphic representation of the median accuracy as function of the mAs. Based on the distribution of the Spearman correlations, the quality (measurement accuracy) was significantly increasing as a function of exposure level for Film and PSP. For CCD, the quality decreased (significantly for CCD-AC) or remained constant. Both for PSP and CCD sensors, measurement accuracy was higher when using a DC tube. Skin doses (μGy) per X-ray unit and exposure time are presented in Fig. 6. The measured dose rates (μGy/s) and kV generation revealed that the AC tube only reached the desired kV levels at certain peaks, that the HF unit gradually increased to reach the desired kV after approximately 20–30 ms, whilst the DC one almost instantly reached its kV after 4–5 ms. The measured exposure time deviated from the chosen setting by 30% to 75% for the AC unit, with increasing error at lower exposures. For the HF and DC unit, this error was <1%.

Relative dose savings were calculated by linking these dosimetry results to the measurement accuracy obtained using the different tubes (see Table 3). Considering an accuracy level of, respectively, 0.5 and 1 mm, dose savings of 27% to 53% with HF and 32% to 55% with DC were found for PSP compared to AC. For CCD, no dose savings were apparent, demonstrating their high sensitivity. For the AC tube (only unit combined with film, serving as a reference), digital PSP systems allowed 15–51% dose saving compared to film, depending on the accuracy level chosen. This is even higher when using CCD sensors (75–90%). The latter allowed 71–79% dose savings compared

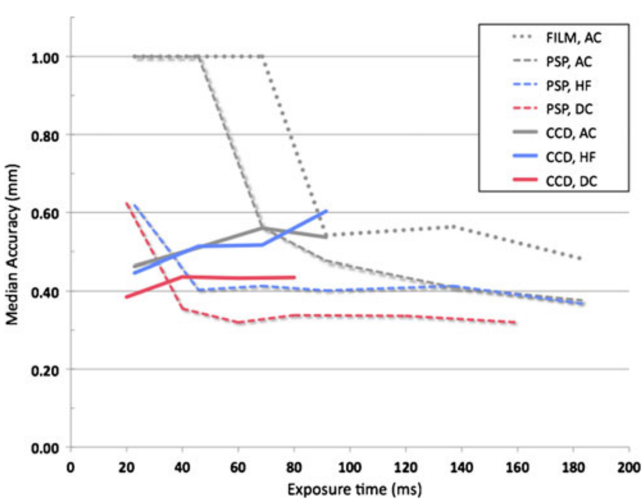

Fig. 5 Median accuracy (absolute distance from gold standard) as a function of exposure time. The exposure time is recalculated from mAs, if mA were equal to 7. Outlying median accuracies (medians higher than 1) are depicted in the figure as *value 1*

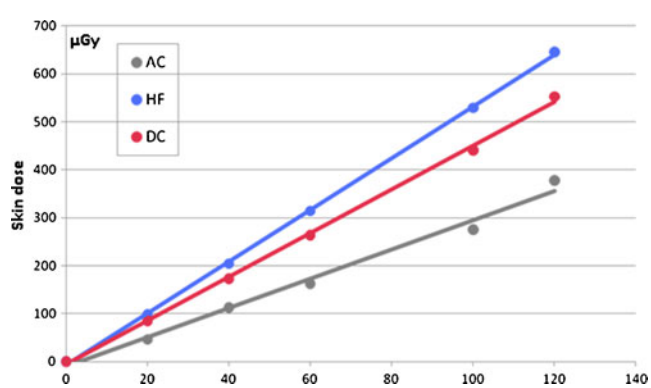

Fig. 6 Skin dose measurements at rising exposure times for the three X-ray tubes: Trophy IRIX 70AC, Planmeca Prostyle-Intra HF and Soredex Minray DC

Table 3 Skin dose comparisons for AC, HF and DC units in combination with film, PSP and CCD at an accuracy of 0.5 and 1 mm

Accuracy	Receptor	AC		HF		DC		Dose savings
		mAs	microGy	mAs	microGy	mAs	microGy	
0.5 mm	Film	1.28	529.2	x	x	x	x	–
	PSP	0.64	257.4	0.32	187.7	0.28	176.3	27–32%
	CCD	0.16	54.5	0.16	90.2	0.14	86.7	None?
			51–90%		52%		51%	
1 mm	Film	0.64	224.1	x	x	x	x	–
	PSP	0.48	190.9	0.16	90.2	0.14	86.7	53–55%
	CCD	0.16	54.5	0.16	90.2	0.14	86.7	None?
			15–76%		None		None	

Relative dose savings for PSP were approximately 27–53% when using HF vs. AC and 32–55% when using the DC tube. No apparent dose saving were seen for CCD sensors (lowest exposure times for the three tubes seemed to deliver adequate accuracy) showing their high sensitivity. The use of a digital system reduces the skin dose needed for accurate measurements (only AC combination with Film was present), but for all tube types at a 0.5-mm accuracy especially CCD sensors allowed further dose savings (approx. 50%) compared to PSP. The [x] represents missing combinations

to PSP, but when using HF or DC, these savings are decreased to approximately 50% for 0.5-mm accuracy and no dose savings at 1-mm accuracy.

Subjective quality evaluation

Figure 7 shows the mean scores for all groups plotted by exposure time for the lamina dura ratings. For the four other subjective ratings, the pattern of results was similar to these ratings. A significant positive relation was observed between exposure level and subjective rating. Statistical comparisons between groups are summarised per observer in Table 4. Irrespective of the type of rating and observer,

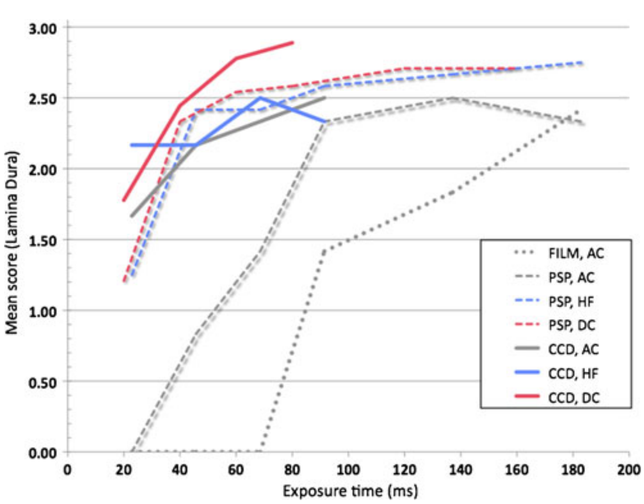

Fig. 7 For the lamina dura, the means of the ordinal scores of each group are plotted by the exposure time, which is recalculated from mAs, if mA were equal to 7. The remainder subjective criteria produced similar graphics

the observed subjective rating was the highest for DC and the lowest for AC. For all variables, the observed subjective rating was significantly higher for DC compared to AC for all observers. DC was only scored significantly higher than the HF unit for lamina dura delineation and trabecular pattern depiction, and only by observer 1. HF was only scored significantly higher than AC for crater and furcation visibility by two observers.

When considering a minimum ordinal score of 2 (=medium visibility) for all variables, dose reductions are comparable to the ones with the bone level measurements (Table 5). Lower exposure times were found when using the HF or DC unit compared to AC, but not for contrast perception using CCD sensors. Dose savings (approximately 50%) were demonstrated when using the latter compared to PSP for lamina dura and bone quality ratings but not for crater and furcation visibility, except using the AC tube. For contrast perception, however, the opposite was found for HF and DC tubes.

Discussion

For the first variable, X-ray generator type, significant differences between measurement accuracy using the AC vs. HF or DC tube were found at low exposure times (between 20 and 80 ms). The HF compared to DC tube was found to produce similar accuracy, however with a significant difference at very low exposure times (between 20 and 40 ms). However, this is only true for PSP systems. Solid-state sensors allowed accurate measurements of periodontal bone levels using the lowest exposure times for all three tubes (see Table 3). This is mainly due to the high sensitivity of these sensors, but may also partially be

Table 4 Comparisons of the subjective quality rating of lamina dura visibility (LD), trabecular depiction (BQ), contrast perception (C), crater (CR) and furcation (FU) visibility

		LD	BQ	C	CR	FU
Obs1	AC vs. HF	$p>0.05$	$p>0.05$	$p>0.05$	$p>0.05$	$p>0.05$
	AC vs. DC	*p<0.005*	*p<0.005*	*p<0.05*	*p<0.05*	*p<0.05*
	HF vs. DC	*p<0.05*	*p<0.05*	$p>0.05$	$p>0.05$	$p>0.05$
Obs2	AC vs. HF	$p>0.05$	*p<0.05*	$p>0.05$	*p<0.05*	*p<0.005*
	AC vs. DC	*p<0.005*	*p<0.05*	*p<0.05*	*p<0.005*	*p<0.005*
	HF vs. DC	$p>0.05$	$p>0.05$	$p>0.05$	$p>0.05$	$p>0.05$
Obs3	AC vs. HF	$p>0.05$	$p>0.05$	*p<0.05*	*p<0.05*	*p<0.05*
	AC vs. DC	*p<0.05*	*p<0.005*	*p<0.0005*	*p<0.005*	*p<0.0005*
	HF vs. DC	$p>0.05$	$p>0.05$	$p>0.05$	$p>0.05$	$p>0.05$

The results are based on the proportional odds model. The significant differences in italics indicate a greater accuracy for the second group vs. the first

explained by the inability to investigate lower tube settings. The AC tube namely revealed large deviations in measured exposure time at low settings (<100 ms), which resulted in the lowest measured dose between the tubes at 20 ms. This still demonstrated adequate accuracy of periodontal measurements and may thus also be the case when lowering HF or DC tubes to this dose level. The differences between tubes for PSP sensors are directly reflecting the beam quality produced by the different tubes where low exposure times produced fewer high-energy photons for AC. The HF unit only needed a small "heat up" time to obtain the desired potential (and further behave similar to a constant potential or DC unit with small ripple).

In current literature, no clinical research has been conducted to investigate the use of HF or DC tubes. McDavid et al. [18] and Helmrot et al/ [17] described dose reductions of, respectively, 26% and 35–40% when using a DC unit instead of a conventional AC one, without loss of radiographic contrast. These studies were laboratory tests using phantoms and do not take into account the receptor and its sensitivity profile. In this study, we could see that accuracy and associated dose savings increased from AC to HF and DC, but only for PSP. Accuracy was determined by bone level measurements deviating from a gold standard. The clinically acceptable deviation for bone loss measurements has been reported—when using a correct standardised radiographic

Table 5 Skin dose comparisons for AC, HF and DC units in combination with film, PSP and CCD at an ordinal score of minimum 2 (=medium visibility)

Variable	Receptor	AC		HF		DC		Dose savings (%)
		mAs	µGy	mAs	µGy	mAs	µGy	
LD	Film	1.28	529.2	x	x	x	x	
	PSP	0.64	257.4	0.32	187.7	0.28	176.3	*27–32*
	CCD	0.32	133.3	0.16	90.2	0.14	86.7	*32–35*
			48–75%		*52%*		*51%*	
BQ	Film	0.96	444.6	x	x	x	x	
	PSP	0.64	257.4	0.32	187.7	0.28	176.3	*27–32*
	CCD	0.48	190.9	0.16	90.2	0.14	86.7	*53–55*
			26–57%		*52%*		*51%*	
C	Film	1.28	529.2	x	x	x	x	
	PSP	1.28	529.2	0.32	187.7	0.28	176.3	*65–67*
	CCD	0.64	257.4	0.48	288.9	0.42	257.8	None?
			0–51%		*–35%**		*–32%**	
CR	Film	0.96	444.6	x	x	x	x	
	PSP	0.96	444.6	0.32	187.7	0.28	176.3	*58–60*
	CCD	0.64	257.4	0.32	187.7	0.28	176.3	*27–32*
			0–42%		*None*		*None*	
FU	Film	1.28	529.2	x	x	x	x	
	PSP	0.96	444.6	0.32	187.7	0.28	176.3	*58–60*
	CCD	0.64	257.4	0.32	187.7	0.28	176.3	*27–32*
			16–51%		*None*		*None*	

The same trend is seen as with the bone level measurements for most variables. For contrast perception with HF and DC tubes in combination with CCD sensors (marked by *), care should be taken since PSP allows lower exposure times for the same perception of radiographic contrast. The relative dose reductions are indicted in italics setup to be <1 mm or even up to 0.5 mm [28]. Considering, respectively, 1- and 0.5-mm deviation, dose savings of 53–55% and 27–32% were found for PSP receptors when using HF or DC units instead of AC. These percentages were in the same range or a bit higher than the mentioned laboratory studies, but also considered the effect of digital sensors (instead of conventional film). In this way, for solid-state sensors (CCD), no apparent dose savings were found, in contrary to PSP receptors.

This brings us to the second variable, the image receptor type, which by itself helps in further dose reductions. For this variable, some studies—however only one for periodontal diagnosis [6]—have explored specific exposure ranges [19–21, 32–35]. Borg and Gröndahl [32] described the wide exposure latitude of PSP systems compared to solid-state sensors, although the latter demonstrated better resolution and require less radiation dose. Berkhout et al. [21] found 30–70% dose reduction with solid-state sensors and 50% with PSP systems when using an older multi-pulse X-ray generator type. In this report, we found 15–51% dose savings for PSP receptors and 76–90% for solid-state sensors when using the AC unit. Borg et al. [19] used a constant potential or DC unit and found useful exposure ranges between 515–1,800 μGy for solid-state sensors and 180–9,110 μGy for PSP systems. These minimal threshold doses for PSP (180 μGy) are similar to the 176.3 μGy found in this study at the 0.5-mm accuracy level (see Table 3). However, for CCD, 515 μGy is considerably higher than our threshold doses with DC, being 86.7 μGy. This difference may be explained by the fast technological advancement over the last few years. The sensors used in Borg's study are older models (1995), whilst the solid-state sensors in this study were more recently introduced (having higher sensitivity and higher resolution, up to 20 lp/mm). Nevertheless, the difference between PSP and solid-state sensors was confirmed in this study with approximately 50% dose savings when using solid-state vs. PSP receptors. At a threshold level of 1 mm, these savings were lost with modern tubes (HF or DC), but not with the conventional AC type. Furthermore, care should be given when using higher exposure times for solid-state sensors. Decreasing accuracy was found for CCD sensors (see Figs. 4 and 5), with even a significant difference ($p<0.01$) compared to PSP when using the AC tube (see Table 2). Whilst PSP receptors showed increasing accuracy at rising exposure times, the contrary was found for solid-state sensors, confirming a more limited useful exposure range of the latter. The reason for this phenomenon may be found in the occurrence of blooming artefacts at high exposure times, which has also been reported in previous studies [19, 21, 33]. These blooming artefacts are typically located at the alveolar crest and cause darkening of the bony crest, which may result in overestimation of periodontal bone loss (see Fig. 3). This was also the reason why most exposure ranges, especially with the DC tube, were kept under 100 ms in this study for solid-state sensors.

For periodontal diagnosis, not only measurement accuracy but also subjective evaluations of periodontal landmarks are important diagnostic criteria [29]. For all evaluated subjective variables, the DC unit scored significantly better than AC. At a threshold rating of 2 (=medium visibility), dose savings were similar to the ones considering measurement accuracy when using HF or DC compared to AC, confirming the previous dose reductions. However, for CCD sensors, lower exposure times with HF or DC tubes did result in higher ratings. Although bone level measurements were possible at the previously discussed low settings, subjective ratings may thus prove to be insufficient. Higher settings were for instance required for adequate contrast perception. Nevertheless, image enhancement for contrast and brightness (window levelling) was not explored in this study and may thus also alter the current findings (also for measurement accuracy) since small under- and overexposure errors might be corrected. The wide dynamic range of PSP receptors was also confirmed here for the contrast variable which scored better at lower exposure times compared to solid-state sensors (see Table 5).

It must be noted that no differentiation between the different film, PSP and CCD image receptors have been made in this report. These might cause small deviations in dose savings for a specific image receptor, but should remain in the same range. This more individual analysis of the current research setup will be explored in a future report.

Lastly, since the introduction of new low-dose imaging modalities in dentistry, like cone beam computed tomography (CBCT), optimisation of current intraoral radiographic protocols with digital sensors becomes even more important for periodontal diagnosis. Modern CBCT units can nowadays image both jaws containing the entire periodontal tissues at very low radiation doses. Vandenberghe et al. [35] found that periodontal bone level measurements were closer to the gold standard when using CBCT 0.4-mm slices compared to digital intraoral radiographic assessment and that crater and furcation depiction was more accurate using CBCT. A recent study from Roberts et al. [36] reported that a CBCT system only required 39.5 μSv for this, which is close to the radiation dose of a full mouth radiographic examination. Ludlow et al. [37] reported the latter to be around 37 μSv when using F-speed film or a PSP system, and Gibbs [38] described effective doses even around 13–100 μSv when using E-speed film. This comparison may somewhat be overrated given the many other CBCT variables, but it should reflect the importance of the required optimisation of intraoral radiographic protocols which should consider the many variables in the radiographic chain, most of which were investigated and discussed in this study.

Conclusion

The present study described the influence of X-ray generator type on the specific exposure settings of digital PSP and CCD sensors (in comparison to film) for periodontal diagnosis. Measurement accuracy of periodontal bone levels was the highest for DC and HF compared to the AC unit. Accepting 0–5 to 1-mm deviation, 27–53% and 32–55% dose savings could be accomplished using, respectively, the HF and DC unit, but only for PSP sensors. These results indicated the high sensitivity of solid-state sensors (compared to PSP). For these CCD sensors, care should be given when using higher exposure times since blooming effects may deteriorate image quality.

The use of a specific image receptor by itself also influenced the dose required for periodontal diagnosis. For each X-ray tube tested, solid-sate sensors allowed radiation dose reductions of approximately 50% compared to PSP. This depended not only on tube type but also on the threshold level used for periodontal accuracy.

For subjective ratings of lamina dura, trabecular pattern, contrast, furcation and crater visibility, similar results were found, but the small deviations should be investigated in future studies where image enhancement is allowed.

Acknowledgements I would like to thank the observers for the many measurements made and Joris Nens for his help with the dosimetry measurements.

Conflict of interest and source of funding The authors have no conflict of interests related to the publication of this article.
No funding has been available other than the author's institution for this research project.

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