Evaluation of image quality parameters of representative intraoral digital radiographic systems

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Objective. The aim of this study was to compare imaging properties of 20 intraoral digital systems objectively.
Study Design. Using a direct current x-ray source and a radiographic phantom, a series of radiographs was made from the lowest exposure time until the sensor saturated. Images were captured and stored. Incident exposures were measured using a radiation meter. Gray scale, spatial resolution, and contrast/detail detectability were evaluated. Presence of 7 distinct steps spanning the gray levels from 0 to 255 was used to define the exposure latitude. An "optimal" exposure, the lowest exposure where maximum spatial resolution and contrast/detail detectability were achieved, was determined.
Results. The systems varied greatly in latitude, "optimal" exposure, and image quality. This may not be readily apparent to the naked eye or when clinical images are compared.
Conclusions. Objective assessment of image quality with a quality assurance tool makes it possible to evaluate and compare the various intraoral digital systems. (Oral Surg Oral Med Oral Pathol Oral Radiol 2013;116:774-783)

Dental radiographs provide a useful aid in the diagnosis and treatment of oral diseases, such as caries, periodontal diseases, root fractures, and oral pathologies.[1] Until the 1980s, these radiographs were obtained using conventional film-based techniques. However, with developments in computer technology and the introduction of digital systems, digital sensors have started gaining popularity in the dental field. The progress has been toward a completely integrated digital environment where digital images can be centrally stored and organized using database systems.[2,3] Although digital x-ray sensors are comparable to analog film for diagnostic tasks, they have several advantages over film radiography. These include immediate image production with solid-state devices, interactive display on a monitor with the ability to enhance image features and make direct measurements, integrated storage with access to images through practice management software systems, security of available backup and off-site archiving, exact radiographic duplicates to accompany referrals, security mechanisms to identify original images and differentiate them from altered images, the ability to tag information such as a patient identifier, date of exposure, and other relevant details, and interoperability of the Digital Imaging and Communications in Medicine file format.[4-7]

Digital intraoral radiography has been in a state of constant change and rapid development since its introduction into the dental market, and its growing acceptance has revolutionized intraoral radiography.[8-10] Based on the image acquisition process, digital radiographic systems are broadly categorized as direct and indirect digital systems. Direct digital systems acquire images with solid-state detectors that are connected to a computer with a wire or wirelessly to produce an image almost instantaneously after exposure. A charge-coupled device (CCD) is a solid-state detector composed of an array of x-ray-sensitive or light-sensitive elements or wells on a silicon chip arranged in a rectangular matrix. In the readout process, the electrons liberated in each element are transferred from one row of wells to the next in a sequential manner. The resulting current is amplified, digitized, and stored as a digital image, which is eventually displayed on a computer monitor.[11] Complementary metal oxide semiconductors active

Authors Mah, Dove, and McDavid are joint developers and inventors of the patented Dental Digital Quality Assurance phantom and method of quality assurance by Dental Imaging Consultants LLC, San Antonio, TX, USA.

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Statement of Clinical Relevance

Although various reports and standards (detailed in the text) suggest that an optimization program is necessary for digital radiographic imaging systems, there have been no published protocols to achieve this goal of producing maximum diagnostic information while minimizing patient dose.

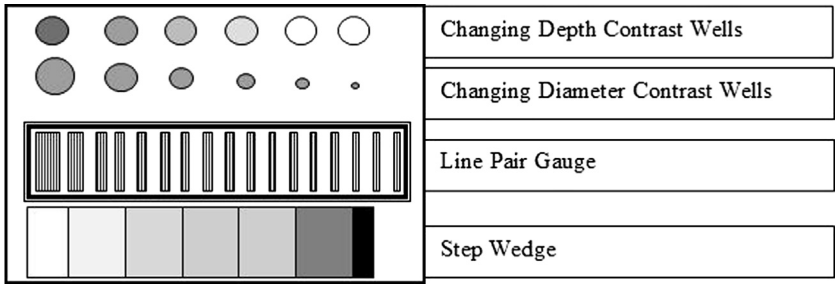

Fig. 1. Schematic representation of the Dental Digital Quality Assurance phantom.

pixel sensors (CMOS-APS) are similar to CCDs except they use an active pixel technology in which the pixels are isolated from their neighbors and are directly accessed individually. Through this technology, the power requirement to process an image is reduced by a factor of 100 compared with CCDs.[12] Indirect digital systems use photostimulable phosphor (PSP) plates. These reusable imaging plates are coated with a radiation-sensitive phosphor, which stores a latent image following x-ray exposure.[13] The plate is scanned using a high-speed laser scanner, and the resulting light emitted by the stimulated phosphor is digitized and converted into displayable electronic information.[14]

Indirect digital systems have some advantages and disadvantages compared with the direct capture imaging modalities. The advantages include wider exposure latitude, flexibility of the plates, similar size and shape as available with conventional film, and the absence of the electric cord.[15] Bedard et al.[15] found that with repeated use of the PSP plates there was a need for the plates to be replaced after only 50 uses to avoid degradation of image quality owing to scratches and surface irregularities. Scratching, fogging, and plate reversals are some additional problems incurred with PSP plates but not seen with direct capture sensors. The prevention of plate reversal problems has been addressed by some PSP systems; namely, the Digora Optime (Soredex, Milwaukee, WI, USA) and Carestream 7600 (Carestream Health Inc, Rochester, NY, USA) systems.

Today a wide variety of intraoral digital systems is available in the dental market.[11,16] The aim of this study was to generate a comprehensive technical report that will provide a detailed comparative analysis of dose, latitude, spatial resolution, and contrast/detail detectability of various intraoral digital systems available commercially in the dental market.

MATERIALS AND METHODS

X-ray source

A Planmeca Intra direct current x-ray source (Planmeca, Helsinki, Finland) was used for the study. This unit has an accelerating potential adjustable from 50 to

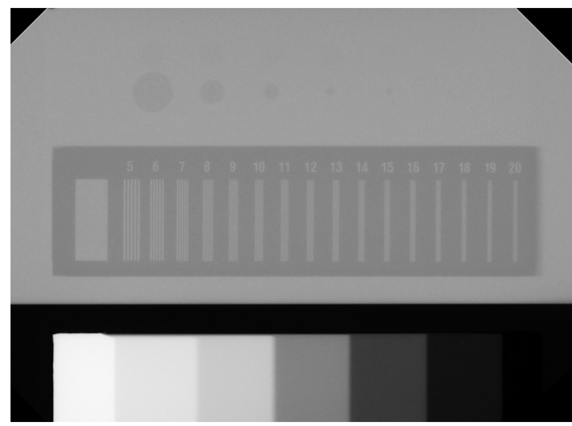

Fig. 2. Sample of a radiographic image of the Dental Digital Quality Assurance phantom.

70 kV, tube current from 2 to 8 mA, and exposure time from 0.01 seconds to 3.20 seconds. Manufacturer presets used for intraoral imaging with the Planmeca Intra are 63 kVp (kilovolt peak) and 8 mA, with varying exposure times for different regions of the oral cavity. Accordingly, this machine was set at 63 kVp and 8 mA for this study.

Radiographic phantom

A Dental Digital Quality Assurance (DDQA) phantom (Dental Imaging Consultants LLC, San Antonio, TX, USA) was used to measure dynamic range, low-contrast detectability, and high-contrast resolution (Figures 1 and 2).[17] A step-wedge made of aluminum alloy of radiologically standard 1100 grade and a piece of lead at one end represents the entire range from no attenuation to full attenuation. Low-contrast detectability is measured using 2 series of 6 round wells (one of varying depth and constant diameter and the other of varying diameters and constant depth) in clear acrylic. High-contrast resolution is measured with a gold foil line pair gauge ranging from 5 to 20 line pairs per millimeter (lp/mm). A 7-mm block of 1100 grade aluminum alloy overlies the line pair gauge and contrast wells to obtain a mid-range exposure level. The

Table I. Overview of digital systems features

System name	Manufacturer	Technology	Interface	Software
Direct capture				
Carestream RVG 6000 Sensor	Carestream Dental (Rochester, NY, USA)	SCMOS	USB	Kodak Dental Imaging software
Carestream RVG 6100 Sensor	Carestream Dental (Rochester, NY, USA)	SCMOS	USB	Kodak Dental Imaging software
Carestream RVG 6500 Sensor	Carestream Dental (Rochester, NY, USA)	SCMOS	USB	Kodak Dental Imaging software
XDR Sensor	XDR (XDR Radiology, Los Angeles, CA, USA)	CMOS	USB	XDR Software
SuniRay Sensor	SUNI (Suni Medical Imaging, San Jose, CA, USA)	CMOS APS	Integrated USB	Prof. Suni software
Visteo Sensor	Owandy USA (Los Angeles, CA, USA)	CMOS induction sensor	USB 2.0 compatible USB 1	Owandy Vision Software
Schick CDR Sensor	Schick Technologies (Long Island City, NY, USA)	CMOS	USB	Schick CDR Software
Schick CDR Elite Sensor	Schick Technologies (Long Island City, NY, USA)	CMOS	USB 2.0	Schick CDR Software
BelGold Sensor	BelGold (Belmont Takara, NJ, USA)	CMOS	USB	Belmont XV Lite Software
Planmeca Prosensor	Planmeca USA (Roselle, IL,USA)	CMOS	USB/Ethernet connection	Romexis
GXS-700	Gendex Dental Systems (Des Plaines, IL, USA)	CMOS	USB 2.0	VixWin Platinum Software
Dexis Platinum Sensor	Dexis LLC (Hatfield, PA, USA)	CMOS	USB	Dexis Imaging software
Dr. Suni Plus Sensor	SUNI (Suni Medical Imaging, San Jose, CA, USA)	CCD	USB 2.0	Prof. Suni software
Dixi 3 (NR & HR)	Planmeca (Roselle, IL, USA)	CCD	USB	Dimaxis 4.5
Accent Barrier (LR & HR)	Air Techniques Inc (Hicksville, NY, USA)	CCD	USB 2.0	Visix Imaging Software
Indirect capture				
Scan-X	Air Techniques Inc (Hicksville, NY, USA)	PSP	USB Connection	Visix Imaging Software
Digora Optime (HR & SHR)	Soredex (Milwaukee, WI, USA)	PSP	Ethernet connection	Digora software
DenOptix QST (NR & HR)	Gendex Dental Systems (Des Plaines, IL, USA)	PSP	USB Connection	Vix Win Software
CS7600 (HS, HR, & SHR)	Carestream Dental (Rochester, NY, USA)	PSP	Ethernet connection	Kodak Dental Imaging software

SCMOS, super complementary metal oxide semiconductor; *CMOS*, complementary metal oxide semiconductor; *CMOS APS*, complementary metal oxide semiconductor active pixel sensor; *CCD*, charge coupled device; *PSP*, photostimulable phosphor plates; *Tiff*, tagged image file format; *USB*, universal serial bus connectors. *NR*, normal resolution; *HR*, high resolution; *LR*, low resolution; *HS*, high speed; *SHR*, super high resolution.

supporting structure utilized to hold the test objects has a large acrylic base with adjustable spring-loaded clamps to center the sensor and hold the sensor perpendicular to the x-ray photon beam. In addition, there are 4 plastic stops for the beam indicating device (BID) to rest on. This assures a uniform source-to-detector distance, which is representative of the clinical situation and ensures a perpendicular alignment to the image receptor.

X-ray meter

A Solo Dent meter (Unfors, Billdal, Sweden) was inserted into the phantom from the top to record entrance exposure. This meter has a sensitivity of 5% or ± 10 μGy (1 millirad) in the 40 to 150 kVp range with a half value layer of 1.5 to 14 mm aluminum.[18]

Digital imaging systems

Sixteen direct digital systems with size 2 solid-state sensors and 4 indirect digital systems with PSP technology were analyzed in this study. The solid-state sensors used in the study were closest in size to the American National Standards Institute's published sizes for "size 2" analog dental film. Table I shows the manufacturer of each system, detector technology, interface, and software.

Carestream Dental has incorporated anatomic filters such as Perio, Endo, and DEJ (for periodontal, endodontic, and dentinoenamel junction optimization, respectively) in their dental imaging software in an effort to manage the image contrast and facilitate the diagnostic accuracy of the clinician. For Carestream RVG sensors (6000, 6100, and 6500), the digital raw

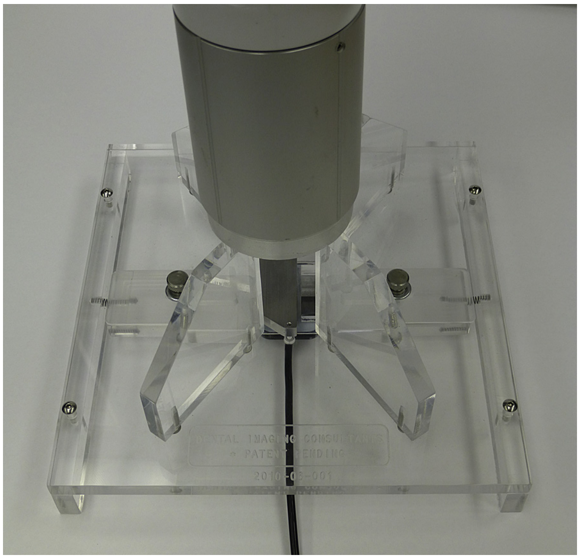

Fig. 3. The Dental Digital Quality Assurance phantom in use.

images were processed by applying these task-specific filters individually to enhance the different zones of interest in the image. For other systems, such as the Planmeca Dixi 3, which has normal-resolution (NR) and high-resolution (HR) modes; the Air Techniques Accent Barrier, which has low-resolution (LR) and high-resolution (HR) modes; and the Dexis Platinum sensor, which has high-resolution (HR) and ultrahigh-resolution (UHR) modes, images were acquired using both of the system's modes.

Digora Optime and DenOptix QST PSP systems have 2 resolution modes, whereas the Carestream CS 7600 PSP system has 3 resolution modes as well as 3 task-specific filters, and the images in all these systems were acquired using these modes.

Digital image acquisition procedure

Each sensor to be evaluated was placed directly under the central portion of the phantom and secured by adjusting the 2 spring-loaded clamps. The BID was placed in contact with the 4 plastic positioning tabs, and a series of exposures was made of the DDQA phantom, from the shortest exposure time of 0.010 seconds to a setting where the detector reached saturation (Figure 3). The digital images were acquired with the manufacturers' proprietary software on a 14.1″ calibrated laptop (D620WXGA, Dell, Roundrock, TX, USA; Windows XP operating system, Microsoft, Redmond, WA, USA) with the resolution set at 1280 × 800 pixels. The native software for each system was utilized for acquiring and storing images in the uncompressed. tiff format in order to avoid loss of information. Entrance exposures were measured at the end of the BID for each exposure time and converted to air kerma values.

Digital image assessment

The images were viewed on a desktop computer (Ultrasharp U2410; Dell) with a 24″ monitor (1920 × 1200 display resolution, 16:10 aspect ratio, and 8-bit color depth). The monitor was calibrated prior to the analysis of images using the Society of Motion Picture and Television Engineers (SMPTE) test pattern. The SMPTE test pattern was used to check for appropriate contrast and brightness settings of the monitor by checking that the 5% and 95% squares on the test pattern were just distinguishable from the 0% and 100% squares.[19,20] This pattern allows the viewer to determine if the linearity (spatial resolution) and aliasing (distortion) of the viewing monitor is within acceptable limits. The images were viewed in an environment with subdued and indirect lighting. No image postprocessing, such as adjustment of brightness or contrast, was applied to the images during image assessment.

Spatial resolution (SR) and contrast/detail detectability (C/D) were measured for all images using image analysis software where applicable (UTHSCSA ImageTool; University of Texas Health Science Center at San Antonio, San Antonio, TX, USA).

Using the measured values of exposure, the exposures at the intraoral imaging receptor were derived for the thickness of aluminum in each step of the step-wedge. The corresponding gray levels were measured for each step of the step-wedge pattern in the image, and a dose-response curve was obtained for each exposure time by plotting the gray level as a function of the exposures as calculated above (Figure 4). An "acceptable" range was established in which all 7 steps of the step-wedge are portrayed as gray levels between 0 and 255. The latitude of each imaging receptor was calculated as the ratio of highest exposure divided by the lowest exposure within the "acceptable range." An "optimal" exposure was identified as the lowest exposure within the acceptable range where the maximum SR and C/D were obtained.

Latitude and optimal exposure, as well as the spatial resolution and contrast/detail detectability at the optimal exposure, were tabulated for the systems included in the study.

RESULTS

Table II shows the consolidated results: latitude, optimal exposure, line pairs per millimeter, the number of visible changing diameter wells, and the number of visible changing depth wells seen in the images acquired from the various digital systems.

Direct digital systems

Complementary metal oxide semiconductors (CMOS) systems.

Carestream Health RVG 6000, RVG 6100, and RVG 6500. Three Carestream systems, RVG 6000, RVG

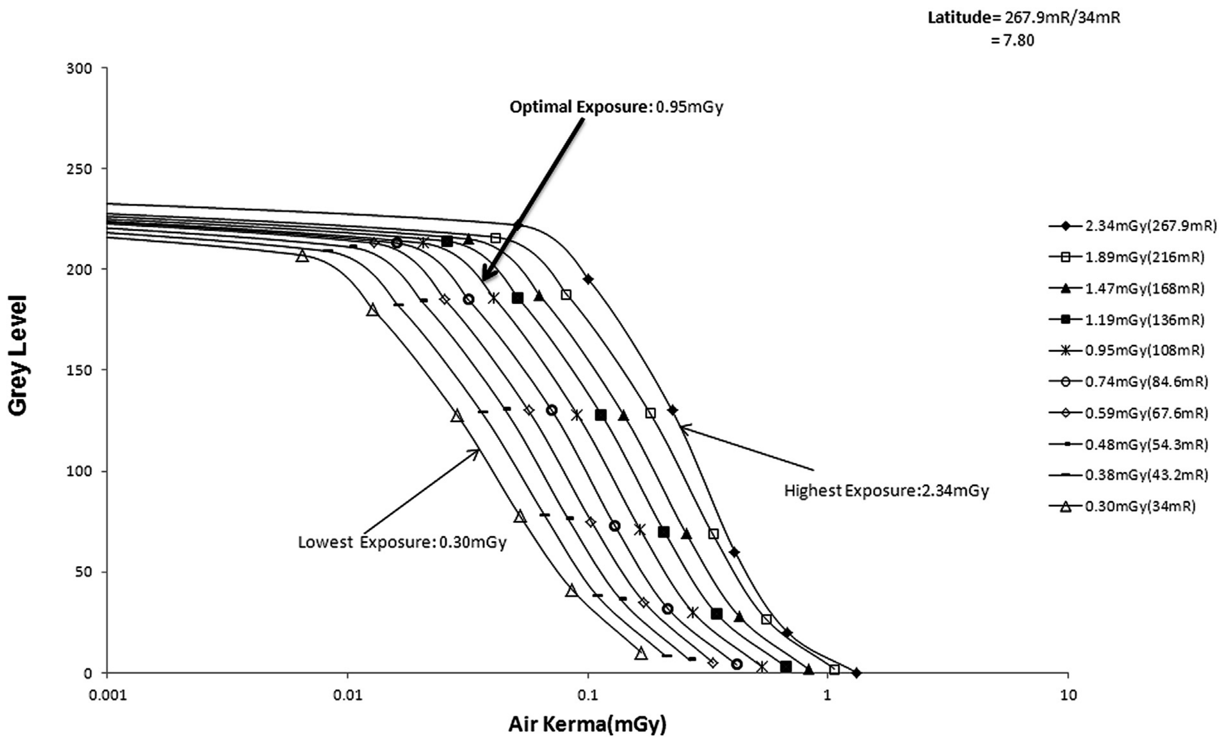

Fig. 4. Sample of dose curves for a digital imaging system.

6100, and RVG 6500, were analyzed separately. Each of these systems has 3 task-specific, predefined image enhancement filters that can be applied at the acquisition stage. These are the periodontal (Perio) mode, which is to optimize visualization of the periodontal tissues, the endodontic (Endo) mode, which is to optimize the contrast values over the entire range, and finally the dentinoenamel junction (DEJ) mode, which is to optimize the values at the crown, the dentinoenamel junction, and the roots. The Endo mode is set by the manufacturer as the default mode of image enhancement.

Consistently, Perio was a better task-specific enhancement mode than the other modes, and the RVG 6100 and 6500 were comparable with, but better than, the RVG 6000 system. The "acceptable" exposure latitude and "optimal" exposures varied widely between the 3 systems and between the image enhancement types. Although the exposures required for optimal image quality vary between the 3 sensors, all the exposures are less than the National Council on Radiation Protection and Measurements (NCRP) Report 172 suggested value of 1.2 mGy for achievable dose.[27]

XDR Sensor, XDR Sensor with Updated Software, and XDR System with a Fiberoptic Faceplate. There was no difference in the overall low-contrast perception, and optimal exposure was 0.95 mGy for all 3 systems. The XDR sensor and the system with updated software both had a highest SR of 13 lp/mm compared with the XDR Sensor with a fiberoptic faceplate, which had an SR of 12 lp/mm. The latitude of the XDR sensor with a fiberoptic faceplate was slightly higher in comparison with the XDR sensor.

SuniRay Sensor. The newer SuniRay Sensor had latitude of 6.56 and was better than the Schick CDR sensor in terms of SR and C/D detectability with lower optimal exposure of 0.38 mGy.

Owandy Visteo Sensor. The Visteo sensor had latitude of 1.24 and an SR of 10 lp/mm when all 7 steps of the step-wedge could be clearly delineated. It never achieved the performance parameters seen with some of the other newer CMOS systems.

Schick CDR Elite Sensor and CDR Sensor. The CDR elite had better low-contrast perceptibility but lower SR (7 lp/mm), whereas the CDR sensor had lower optimal exposure (0.38 mGy) with better SR (9 lp/mm).

Belmont Belgold Sensor. The Belgold sensor had a latitude of 3.10 and poor low-contrast perceptibility, with an SR of 11 lp/mm.

Planmeca Prosensor. The Planmeca Prosensor with Ethernet and USB connection had the same SR of 10 lp/mm as the Visteo and SuniRay sensors but had

Table II. Overview of evaluated parameters from digital systems

Direct digital system	*Sensor type*	*Image enhancement types*	*Latitude (highest exposure/ lowest exposure)*	*Optimal exposure (mGy)*	*lp/mm (SR)*	*Δ Dia. wells**	*ΔDep. wells†*
RVG 6000	CMOS	Perio Mode	6.38	0.74	14	5	2
		Endo Mode	5.07	0.95	13	6	2
		DEJ Mode	2.02	0.48	12	5	1
RVG 6100	CMOS	Perio Mode	5.07	1.19	13	5	4
		Endo Mode	5.07	0.48	10	5	2
		DEJ Mode	1.00	0.74	11	5	3
RVG 6500	CMOS	Perio Mode	3.18	0.95	15	6	4
		Endo Mode	2.61	0.59	14	6	4
		DEJ Mode	1.60	0.59	13	6	4
XDR Sensor	CMOS		6.35	0.95	13	5	4
		With updated software	6.35	0.95	13	6	4
		With fiberoptic faceplate	7.80	0.95	12	6	4
SuniRay Sensor	CMOS		6.56	0.38	10	4	3
Visteo Sensor	CMOS		1.24	0.59	10	4	3
CDR Elite Sensor	CMOS		2.51	0.74	7	5	1
CDR sensor	CMOS		1.27	0.38	9	4	0
BelGold Sensor	CMOS		3.10	1.47	11	5	0
Planmeca Prosensor	CMOS	With Ethernet and USB connection	10.26	0.48	10	5	3
GX-S700 Sensor	CMOS		50.83	1.19	14	6	4
Dexis Platinum Sensor	CMOS	High Resolution (HR)	50.83	0.95	13	6	4
		Ultra High Resolution (UHR)	50.83	0.95	15	6	5
Dr. Suni Plus sensor	CCD		10.00	0.74	8	4	0
Dixi 3 Sensor	CCD	Normal Resolution (NR)	12.84	0.48	7	4	2
		High Resolution (HR)	6.22	0.48	12	5	3
Accent Barrier Sensor	CCD	Low Resolution (LR)	1.26	0.38	7	5	2
		High Resolution (HR)	1.27	0.38	8	5	2
Indirect digital system	*Sensor type*	*Image enhancement types*	*Latitude (highest exposure/ lowest exposure)*	*Optimal exposure*	*lp/mm*	*Δ Dia. Wells**	*ΔDepth wells†*
Scan-X	PSP Plate	______	24.80	1.47	7	5	3
Digora Optime	PSP Plate	High Resolution (HR)	12.58	0.74	6	5	2
		Super High Resolution (SHR)	12.58	1.19	8	5	2
Den Optix QST	PSP Plate	Normal Resolution (NR)	63.79	1.19	7	5	3
		High Resolution (HR)	63.79	1.19	8	6	3
CS7600	PSP Plate	ENDO/HS	3.96	0.74	6	5	0
		ENDO/HR	4.93	0.59	7	5	3
		ENDO/SHR	6.20	0.48	10	6	1
	PSP Plate	PERIO/HS	2.48	0.74	6	5	3
		PERIO/ HR	3.96	0.59	7	5	3
		PERIO/ SHR	7.88	0.48	10	6	4
	PSP Plate	DEJ/ HS	1.56	0.95	6	5	0
		DEJ/ HR	2.48	1.19	8	6	1
		DEJ/ SHR	3.96	0.74	10	6	1

DR, dynamic range; *SR*, spatial resolution; *C/D*, contrast-detail; *lp/mm*, line pair per millimeter; *HS*, high speed.
*Change in diameter wells.
†Change in depth wells.
NOTE. Estimate of Error SR +/− 1 lp/mm.

slightly better low-contrast perceptibility than the other 2 sensors.

Gendex GSX-700 Sensor. The GSX-700 sensor had an overall better SR of 14 lp/mm, better C/D detectability, and a wide latitude (50.83), very similar to Dexis Platinum sensor (HR and UHR modes).

Dexis Platinum Sensor. Both the HR and UHR modes of this sensor had a wide latitude of 50.83, with better low-contrast perceptibility and an SR ranging from 13 to 15 lp/mm.

CCD systems.

SuniPlus Sensor. The SuniPlus sensor performance was poor in comparison with SuniRay, with optimal exposure of 0.74 mGy and an SR of 8 lp/mm.

Planmeca Dixi 3 Sensor. The Dixi 3 Sensor (CCD) has 2 image capture modes: normal-resolution (NR) and high-resolution (HR). There was a clear difference noted when images were captured in the HR mode, with 12 lp/mm, in comparison with 7 lp/mm when captured in the NR mode. In addition, the low-contrast perceptibility was clearly greater with the HR mode than with the NR mode. The optimal exposure was the same 0.48 mGy in both modes.

Accent Barrier Sensor. The Accent Barrier sensor has 2 image capture modes: low-resolution (LR) and high-resolution (HR). The SR was slightly better in the HR mode than in the LR mode. There was no clear difference noted in the C/D detectability between the 2 modes. The optimal exposure was the same 0.38 mGy in both modes and was lower than those in the other CCD systems, such as the Dixi 3 (0.48 mGy) and Dr. SuniPlus (0.74 mGy) sensors.

Indirect digital Systems

Photostimulable phosphor plate systems. In this study, we evaluated 4 different commercially available indirect capture intraoral PSP plate systems. These included the Scan-X system (Air Techniques); Digora Optime system (Soredex); DenOptix QST system (Gendex), and Carestream CS7600 (Carestream Dental).

Air Techniques Scan-X System. Although the Air Techniques Scan-X had wide latitude (24.80) and good low-contrast perceptibility, it performed poorly in terms of SR at only 7 lp/mm, similar to other PSP systems.

Digora Optime System. The Digora Optime has 2 image capture modes: high-resolution (HR) and super-high-resolution (SHR). There was a clear difference noted when images were captured in the HR mode, with 6 lp/mm, in comparison with 8 lp/mm in the SHR mode. It had a latitude of 12.58, with the lowest exposure being 0.19 mGy and the highest being 2.35 mGy, which is above the diagnostic reference level as set out in NCRP Report 172 but still within the limits set by most state regulations.

Gendex DenOptix QST System. The DenOptix QST has 2 image capture modes: normal-resolution (NR) and high-resolution (HR). The SR was 7 lp/mm at NR and 8 lp/mm when images were acquired using the HR mode. In general, it had the widest latitude (63.79) among the 4 PSP systems.

Carestream Health CS7600 System. The CS7600 has 3 image capture modes: high-speed (HS), high-resolution (HR), and super-high-resolution (SHR). In addition, it also has 3 task-specific filter modes: Perio, Endo, and DEJ (as explained earlier).

All 3 task-specific filters in the SHR capture mode had highest SR of 10 lp/mm with a highest C/D detectability in the Perio filter mode. The HS capture mode had the lowest SR (6 lp/mm) with all 3 task-specific filters and an SR of 8 lp/mm with HR capture mode and DEJ filter. In general, the CS7600 had the lowest latitude among the 4 PSP systems.

DISCUSSION

Since the early 1980s, digital imaging has become one of the fastest-growing areas in dentistry. A wide variety of newer intraoral digital sensors and PSP systems are entering the marketplace at a startling rate. As new technologies become available, they need to be evaluated prior to being applied in the clinical setting. The literature has proposed various procedures for evaluation. One such proposal was put forth by Fryback and Thornbury.[21] They proposed the adoption of the hierarchical approach, starting at a technical level (image/technical efficacy) and ending with the benefits to society at large (societal efficacy).[21] However, the scientific publications and unbiased data that are available for the multitude of digital imaging systems are still sparse. Clinicians have a limited amount of knowledge regarding the relationship between the imaging systems' characteristics and clinical outcomes; this creates a high demand for diagnostic efficacy testing and quality assurance testing.[22] In this study, we evaluated the latitude and optimal exposure settings as well as the C/D detectability and SR at the optimal settings for 20 commercially available intraoral digital systems. We also demonstrated a means of assuring that exposure settings selected for clinical use provide the maximal image quality with minimal exposure to the patient, in keeping with the principle of "as low as reasonably achievable" (ALARA), which is cited in various reports of the NCRP, the International Commission on Radiological Protection (ICRP), and others,[23-27] including ICRP 73,[24] ICRP 93,[25] NCRP Report 145,[26] and NCRP Report 172.[27]

Latitude is the range of exposures that will produce images within the useful gray level range.[28] Using our definition, the ratio of the highest exposure to the lowest exposure within the "acceptable" range, all 4 PSP systems showed wide latitude. The DenOptix PSP system (Gendex) had slightly greater latitude of 63.79. Out of the 3 CCD systems tested, the Accent Barrier sensor had the lowest latitude, at 1.26. Of the 11 CMOS systems tested in this study, 2 systems showed wider latitude: the Dexis Platinum (50.83) and the Gendex GX-S700 sensor (50.83). The other CMOS systems whose latitudes were good were the Planmeca Prosensor; the XDR with a fiberoptic face plate; the RVG 6100, RVG 6500, and RVG 6000; and the SuniRay. The Visteo, CDR, CDR Elite, and Belgold showed narrow latitude. Studies conducted in the past have shown that PSPs have the widest latitude in comparison with CCD and CMOS sensors, which allows a high tolerance for variations in exposure techniques, often requiring fewer retakes.[29-31] It is important to recognize that high latitude is not necessarily desirable, because it makes possible deviations from the optimal exposure, which may appear acceptable to the clinician while either overexposing the patient at the high end of the scale or yielding noisy images lacking in diagnostic quality at the low end.

Another factor of paramount importance when it comes to assessing image quality is SR. It is the ability for distinguishing the fine details in an image. This is expressed as the number of line pairs per millimeter.[32] The SR of the 11 CMOS systems analyzed in this study ranged from as low as 7 lp/mm (CDR Elite) to as high as 15 lp/mm (RVG 6500/Perio mode; Dexis Platinum/SHR mode), whereas that of the 3 CCD systems ranged from 7 lp/mm (Accent Barrier/LR) to 12 lp/mm (Dixi 3/HR). The 4 PSP systems ranged from 6 lp/mm (CS7600/HS mode; Digora Optime/HR mode) to 10 lp/mm (CS7600/SHR mode). The SR of the CS7600 DEJ, Endo, and Perio task-specific filters and the various resolution modes varied slightly from 6 lp/mm (HS) to 10 lp/mm (SHR). Studies done for detection of proximal caries have shown that higher-SR images do not improve the detection of caries in a PSP system and also that caries diagnostic accuracy seems to be little influenced by an increase in SR and bit depth from 8-bit to 12-bit or 16-bit within the digital radiographic system brands.[33,34] On the contrary; de Oliveira et al.[35] found that a combination of endodontic filter with higher SR and higher contrast resolution is recommended for determination of file lengths when using storage phosphor plates. Another subjective image quality comparison study between the Schick CMOS and CCD detectors showed that the radiographic images were of similar overall quality and that the CMOS sensor outperformed its CCD predecessor for depiction of cortical bone and root apices, whereas the CCD detector was only rated superior for depiction of root canal space.[36] However, the results of our study show that the application of the various resolution modes and task-specific filters produce objective effects on image quality, which can have an effect on the probability of accurately evaluating the most common diagnostic tasks, such as caries detection, endodontic file length determination, or root canal morphology visualization. However, most intraoral radiographic images are not task-specific and are used for multiple diagnostic tasks. For example, a posterior bitewing radiograph may be used both for the detection of proximal caries and for the assessment of crestal bone loss. Using task-specific filter algorithms for image quality enhancements has a potential to discard important data.

The manufacturers' claims of theoretical resolution based on the pixel dimensions were not confirmed on any imaging system. With direct digital systems, the theoretical resolution is determined by the pixel size; thus, to get a higher resolution, the pixel size needs to be smaller. At the same time, the actual resolution is considerably lower than the theoretical resolution, owing to electronic noise and diffusion of photons within the scintillator coating or to imperfections in the coupling systems of the fiberoptics.[32]

Another important factor during the acquisition of digital radiographic images is contrast resolution (CR). CR is the ability to distinguish different densities within a radiographic image. Most of the diagnostic tasks in dentistry require a large degree of C/D perceptibility. Diagnostic accuracy is influenced by kilovolt peak of x-ray exposure and bit depth of the receptor of the digital radiographic system.[37] The higher the bit depth, the greater the CR, allowing for a greater display of the subtle changes in the radiographic images. For example, to diagnose the periodontal bone levels, adequate contrast may be crucial for accurate visualization of the alveolar crest, which can be easily deteriorated by blooming artifacts.[38-40] Earlier digital systems produced 8-bit images; however, newer systems are capable of generating 12-bit and 16-bit images. Whereas standard computer monitors can only image 256 gray shades, the human eye can also only discern approximately 10 to 13 lp/mm or 60 shades of gray at once without any aids.[41] The results of our study clearly showed that the Dexis Platinum, the XDR sensor with a fiberoptic face plate, the RVG 6500, and the GX-S700 sensor have higher low-C/D perceptibility than the RVG 6100 (Endo), the Belgold sensor, the CDR Elite, the Planmeca Prosensor (with both Ethernet and USB interfaces), the SuniPlus, and the Dixi 3 (with both NR and HR).

A previous study by Li et al.[42] surveyed end-user opinions on dental digital sensor characteristics in preparation for the design of a new x-ray imaging sensor and found that the most desired characteristic for a new sensor was contrast resolution. This was followed by imaging noise and SR, clearly indicating that practitioners demand a new digital imaging system that is capable of producing high-quality images. In addition, caries, periapical and periodontal features, and bone lesions in intraoral radiographs were the most frequently mentioned dental features to be enhanced by digital sensors, suggesting the requirement for a task-specific intraoral imaging system. Although digital imaging systems cannot duplicate all the image properties of film, they should be able to provide sufficient information for accurate diagnoses. In order to achieve this, both SR and contrast resolution need to be adequate, and patient doses should not exceed those required with the fastest available film-based systems.

The present study provides data for assessing the various characteristics desired in intraoral digital radiography in systems presently on the market. It also provides a methodology that may be applied in the evaluation of future systems as they become available.

CONCLUSION

An ideal intraoral digital system should have good spatial resolution, good contrast detail detectability, and a good dose-response curve over a wide range of exposures. This study shows that the various intraoral digital systems that come into the market vary markedly from one another in these properties. Since this is not readily apparent to the naked eye or when teeth are radiographed, a quality assurance tool such as the DDQA phantom serves as a useful aid for clinicians who wish to derive this information for any intraoral digital imaging system.

REFERENCES

1. Cederberg R. Intraoral digital radiography: elements of effective imaging. *Compend Contin Educ Dent*. 2012;33:656-658, 662, 664.
2. Whaites E. *Essentials of Dental Radiography and Radiology*. 3rd ed. London, England: Churchill Livingstone; 2002:199-204.
3. Wenzel A. Two decades of computerized information technologies in dental radiography. *J Dent Res*. 2002;81:590-593.
4. Farman AG, Levato CM, Gane D, Scarfe WC. In Practice: how going digital will affect the dental office. *JADA*. 2008;139(suppl 3):14S-19S.
5. Wenzel A, Møystad A. Work flow with digital intraoral radiography: a systematic review. *Act Odontol Scand*. 2010;68:106-114.
6. Farman AG. Use and implication of the DICOM standard in dentistry. *Dent Clin North Am*. 2002;46:565-573.
7. Decker JD, Bollen A, Chen CSK. A model for digital archiving of radiographs into a searchable database. *Am J Orthod Dentofacial Orthop*. 2007;132:856-859.
8. Wenzel A. A review of dentists' use of digital radiography and caries diagnosis with digital systems. *Dentomaxillofac Radiol*. 2006;35:307-314.
9. Dunn SM, Kantor ML. Digital radiology: facts and fictions. *J Am Dent Assoc*. 1993;124:38-47.
10. Vandre RH, Webber RL. Future trends in dental radiology. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod*. 1995;80:471-478.
11. Sanderink GC, Miles DA. Intraoral detectors. CCD, CMOS, TFT, and other devices. *Dent Clin North Am*. 2000;44:249-255.
12. Paurazas SB, Geist JR, Pink FE, et al. Comparison of diagnostic accuracy of digital imaging using CCD and CMOS-APS sensors with E-speed film in the detection of periapical bony lesions. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod*. 2000;89:356-362.
13. Kashima I. Computed radiography with photostimulable phosphor in oral and maxillofacial radiology. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod*. 1995;80:577-598.
14. Sonoda M, Takano M, Miyahara J, Kato H. Computed radiography utilizing scanning laser stimulated luminescence. *Radiology*. 1983;148:833-838.
15. Bedard A, Davis TD, Angelopoulos C. Storage phosphor plates: how durable are they as a digital dental radiographic system? *J Contemp Dent Pract*. 2004;5:57-69.
16. Farman AG, Farman TT. A comparison of 18 different x-ray detectors currently used in dentistry. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod*. 2005;99:485-489.
17. Mah P, McDavid WD, Dove SB. QA Phantom for digital dental imaging. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod*. 2011;112:632-639; e-pub 2011 Sep 8.
18. Unfors technique specification brochure. Available at: http://www.raysafe.com/Products/Equipment/RaySafe%20Solo.
19. Wade C, Brenan PC. Assessment of monitor conditions for the display of radiological diagnostic images and ambient lighting. *Br J Radiol*. 2004;77:465-471.
20. Gray J. Use of the SMPTE test pattern in picture archiving and communication systems. *J Digit Imaging*. 1992;5:54-58.
21. Fryback DG, Thornbury JR. The efficacy of diagnostic imaging. *Med Decis Making*. 1991;11:88-94.
22. Webber RL. The future of dental imaging: where do we go from here? *Dentomaxillofac Radiol*. 1999;28:62-65.
23. Eastman TR. ALARA and digital imaging systems. *Radiol Technol*. 2013;84:297-298.
24. International Commission on Radiological Protection. Radiological protection and safety in medicine, ICRP report 73. *Ann ICRP*. 2004:34.
25. International Commission on Radiological Protection. Managing patient dose in digital radiology, ICRP Publication 93. *Ann ICRP*. 2004:34.
26. National Council on Radiation Protection and Measurements. Radiation Protection in Dentistry, NCRP Report No. 145.
27. National Council on Radiation Protection and Measurements. Reference Levels and Achievable Doses in Medical and Dental Imaging: Recommendations for the United States. NCRP Report No. 172.
28. Razmus TF. Image receptors and producing diagnostic quality images. In: Razmus TF, Williamson GF, eds. *Current Oral and Maxillofacial Imaging*. Philadelphia, PA: WB Saunders; 1996:60-65.
29. Doyle P, Finney L. Performance evaluation and testing of digital intra-oral radiographic systems. *Radiat Prot Dosimetry*. 2005;117:313-317.
30. Borg E, Attaelmanan A, Grondahl HG. Image plate systems differ in physical performance. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod*. 2000;89:118-124.
31. Goshima T, Goshima Y, Scarfe WC, Farman AG. Sensitometric response of the Sens-A-Ray, a charge coupled imaging device, to changes in beam energy. *Dentomaxillofac Radiol*. 1996;25:17-18.
32. Ludlow JB, Mol A. Digital imaging. In: White SC, Pharoah MJ, eds. *Oral Radiology: Principles and Interpretation*. 6th ed. St Louis, MO: Mosby; 2009:78-99.
33. Li G, Berkhout WER, Sanderink GC, Martins M, van der Stelt PF. Detection of in vitro proximal caries in storage phosphor plate radiographs scanned with different resolutions. *Dentomaxillofac Radiol*. 2008;37:325-329.
34. Wenzel A, Haiter-Neto F, Gotfredsen E. Influence of spatial resolution and bit depth on detection of small caries lesions with digital receptors. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod*. 2007;103:418-422.
35. de Oliveira ML, Pinto GC, Ambrosano GM, Tosoni GM. Effect of combined digital imaging parameters on endodontic file measurements. *J Endod*. 2012;38:1404-1407.
36. Kitagawa H, Scheetz JP, Farman AG. Comparison of complementary metal oxide semiconductor and charge-coupled device

intraoral X-ray detectors using subjective image quality. *Dentomaxillofac Radiol*. 2003;32:408-411.
37. Heo MS, Choi DH, Benavides E, et al. Effect of bit depth and kVp of digital radiography for detection of subtle differences. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod*. 2009;108:278-283.
38. Vandenberghe B, Fieuws S, Bosmans H, Yang J, Jacobs R. 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. *Clin Oral Investig*. 2010; http://dx.doi.org/10.1007/s00784-010-0416-8.
39. Berkhout WE, Beuger DA, Sanderink GC, van der Stelt PF. The dynamic range of digital radiographic systems: dose reduction or risk of overexposure? *Dentomaxillofac Radiol*. 2004;33:1-5.
40. Borg E, Attaelmanan A, Gröndahl HG. Subjective image quality of solid-state and photostimulable storage phosphor systems for digital intra-oral radiography. *Dentomaxillofac Radiol*. 2000;29:70-75.
41. Künzel A, Scherkowski D, Willers R, Becker J. Visually detectable resolution of intraoral dental films. *Dentomaxillofac Radiol*. 2003;32:385-389.
42. Li G, van der Stelt PF, Verheij JG, et al. End-user survey for digital sensor characteristics: a pilot questionnaire study. *Dentomaxillofac Radiol*. 2006;35:147-151.

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