Investigation

Improvements in image quality after optimization in digital intraoral radiographs

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ABSTRACT

Background. Digital intraoral radiographic exposures are optimized largely on the basis of subjective assessment of diagnostic image quality. This study presents an objective approach to optimize radiographic exposure settings for digital intraoral radiographic systems.

Methods. Seven size 2 digital intraoral systems were assessed for image quality and determination of optimal exposure after the protocol specified in *American National Stnadard/American Dental Association Standard No. 1094: Quality Assurance for Digital Intra-Oral Radiographic Systems*. A ProX radiograph unit (Planmeca) at 63 kVp and 6 mA was used to obtain radiographs of the Dental Digital Quality Assurance phantom. ImageJ software (National Institutes of Health) was used to quantify dynamic range and spatial resolution, and contrast perceptibility was evaluated visually. Optimal exposure is the setting with the maximal contrast perceptibility and spatial resolution while displaying the full dynamic range. After image optimization, a custom phantom consisting of an endodontically prepared tooth was imaged to evaluate the file position relative to the apex for each system. Differences in distances between file position relative to the root apex at the optimal exposure as well as 1 increment above and below were measured.

Results. Radiographic images obtained at the optimal exposure yielded better visualization and more accurate measurements of the file tip relative to the apex.

Conclusions. Optimizing radiographic exposures improves image quality and accuracy in clinical decisions.

Practical Implications. Improvement in image quality and better accuracy in actual distance of the endodontic file to the radiographic apex coupled with complete cleaning, shaping, and obturation of the canal should lead to better endodontic treatment outcomes.

Key Words. Quality control; quality assurance; image optimization; digital radiography; exposure optimization; radiographic phantom; image analysis.

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Dental radiographic imaging is an integral component in assessment of dental health. Dentists often base diagnoses and treatment decisions on information obtained from radiographic examinations. Radiographs provide valuable information on dental disease including caries, periodontal bone loss, and periapical disease, which could not otherwise be observed via clinical examination. In the past 2 decades, digital imaging has become the predominant radiographic system used by practicing dentists in the United States, with 86% of offices using digital intraoral imaging.[1] There are variations in technical specifications and software of commercial intraoral digital imaging systems, leading to marked variation in image quality among dental sensors.[2]

To provide dental offices with instruction on image quality and image optimization, in 2020 the American Dental Association Standards Council for Dental Informatics published *American National Standard/American Dental Association Standard No. 1094: Quality Assurance for Digital Intra-Oral Radiographic Systems* (Standard 1094).[3] Standard 1094 identifies 3 components of digital intraoral imaging systems that must be monitored periodically to ensure optimal performance: the image display, the x-ray source, and the image receptor.[3] First, the image viewing environment should be optimized; images should be viewed with reduced ambient light and appropriate masking of the screen so that most of the light from the display is from the digital image itself. Image display devices, for

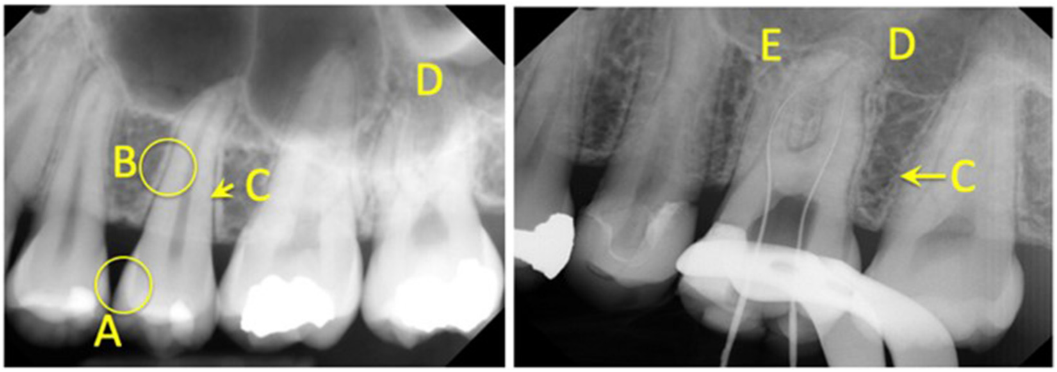

Figure 1. Multiple diagnostic applications associated with a single periapical radiograph. **A**. Caries diagnosis: contrast resolution. **B**. Identify lamina dura: contrast resolution. **C**. Identify periodontal ligament space (≈200 μm). **D**. Assess periapical bone: contrast resolution. **E**. Identify size of no. 6 0.02 K-file.

example computer monitors, and the display software should be adjusted to optimize brightness and contrast, using a Society of Motion Picture and Television Engineers test image pattern.[4] Second, intraoral x-ray sources should be evaluated regularly for consistency and acceptable variance in beam energy (kVp), x-ray output intensity (mGy), beam quality (measured as half-value layer thickness of aluminum), exposure time (ms), and accuracy of x-ray beam collimation.[5] Together, these parameters ensure consistent function of the x-ray generator, an essential element for consistent image quality. Third, digital image receptors must be monitored periodically, either qualitatively or quantitatively, using a radiographic phantom that simulates the geometry of intraoral imaging clinically.

Digital imaging technology, unlike radiographic film, has a wide latitude, which allows dentists to make esthetically acceptable images even at considerably high exposures.[6] A basic premise of optimizing radiologic imaging protocols is to use the least amount of radiation that will produce a diagnostically acceptable image. This premise has guided the concepts of diagnostic reference levels (DRLs) and achievable doses,[7] which provide practitioners with benchmarks for comparison while maintaining diagnostic quality. Benchmark doses for intraoral imaging are published in the National Council of Radiation Protection and Measurements reports nos. 172 and 177.[7,8]

A principal advantage of digital imaging is the ability to adjust image density and contrast to facilitate diagnostic assessments required.[6] Image optimization allows these different diagnostic assessments to be performed at the maximum capability of the receptor and imaging system, thus providing the clinician with the highest-quality image for all the assessments needed. A single intraoral radiograph often serves multiple diagnostic objectives, underscoring the need for producing images that will provide all information adequately. This is illustrated in Figure 1. However, the need for this optimization and its impact on clinical image quality has not been described clearly in the literature.

In this article, we examine the value of applying image optimization as specified in Standard 1094 to provide better-quality radiographic images for diagnostic decisions. We evaluated a common clinical diagnostic task, namely, the measurement of distance from an endodontic file tip to the radiographic apex to ensure complete instrumentation of a root canal, for accuracy between optimal exposure and 1 increment above and below the optimal exposure. The null hypothesis is that image optimization does not produce a better diagnostic image and there is no measurable difference in the distance between the file tip and apex among the 3 different radiographic exposure situations.

METHODS

We followed the protocol in Standard 1094 for assessment and comparison of image quality from 7 different digital imaging systems.[5] The details of the components of the imaging systems are described below.

Intraoral x-ray source

We used a ProX intraoral radiograph unit with a 0.4-mm focal spot (Planmeca). We made exposures at 63 kVp (constant potential) and tube current 6 mA with a 30-cm cone length. We measured the x-ray output at the end of the beam-indicating device using a calibrated Raysafe Unfors ThinX radiation meter (Fluke Biomedical).

ABBREVIATION KEY

CMOS:	Complementary metal-oxide semiconductor.
DDQA:	Digital Dental Quality Assurance.
DRL:	Diagnostic reference level.
USB:	Universal Serial Bus.

Display monitor and viewing conditions

We performed all radiographic image assessment using a Dell Ultrasharp (Dell Roundrock) monitor in a room with reduced ambient lighting. Before use, we assessed the monitor luminance and contrast using the Society of Motion Picture and Television Editors medical display monitor calibration pattern as specified in Standard 1094[3-5] and adjusted the settings if needed. The images were displayed such that most of the lighting originated from the displayed image.

Digital sensors

We examined 7 digital imaging systems, listed in alphabetic order: Carestream 6200 (Carestream Dental), Dexis Platinum (Kavo Dental), Gendex GXS-700 (Kavo Dental), LED Tuxedo (Apteryx Imaging), Planmeca ProSensor HD (Planmeca USA), Schick 33 (Dentsply Sirona), and XDR (XDR Radiology). Table 1 lists the specifications for all the digital imaging systems evaluated.

All 7 intraoral radiographic sensors were size 2 receptors with many similarities in design such as a cesium iodide scintillator, fiber-optic plate, complementary metal-oxide semiconductor pixel matrix, analog-to-digital convertor, and Universal Serial Bus 2.0 connector to the computer. The 7 digital imaging sensors were new with no previous clinical use and were validated using the acceptance test described in Standard 1094. All 7 of the intraoral radiographic receptors were evaluated using the manufacturer's native software, and all image-processing settings were turned off or decreased to the lowest possible setting.

Intraoral radiographic phantom

As specified in Standard 1094, we assessed the dynamic range, spatial resolution, and contrast resolution of each digital image. The Digital Dental Quality Assurance (DDQA) phantom (Dental Imaging Consultants) was used to obtain all 3 parameters on a single image (Figure 2). The phantom has been previously validated for dental imaging parameters.[2,9-12]

Image acquisition

Image receptors were positioned in the DDQA phantom per the manufacturer's instructions with the x-ray beam perpendicular to the sensor, and all exposures were made at the same geometry to allow comparison. We obtained a series of radiographic exposures from 0.01 through 0.8 s or until the image receptor was saturated with photons. We determined an image receptor to have become saturated when the last step on the step-wedge pattern was no longer visible on the radiographic image. We used the same laptop computer for all image acquisitions and exported the images in TIFF format for radiographic image assessment.

Image quality analysis

We subjectively scored contrast perceptibility via visual observation of the contrast wells in the DDQA phantom (Figure 2) and recorded the number of contrast wells that were perceptible to the observer. To measure spatial resolution, we used ImageJ (National Institutes of Health), an image analysis program. We placed a 100-pixel wide line over the line pair resolution pattern to depict the

Table 1. Digital imaging systems specifications.

DIGITAL IMAGING SYSTEM	MANUFACTURER	SENSOR TYPE	BIT DEPTH	COMPUTER INTERFACE	SOFTWARE
Carestream 6200	Carestream Dental	CMOS[*]	12	Direct USB[†] 2.0	CS Imaging
Dexis Platinum	Kavo Dental	CMOS	14	Direct USB 2.0	Dexis Imaging
Gendex GXS-700	Kavo Dental	CMOS	12	Direct USB 2.0	VixWin Platinum Software
LED Tuxedo	Apteryx Imaging	CMOS	12	Direct USB 2.0	Apteryx Lite
Planmeca ProSensor HD	Planmeca USA	CMOS	12	Indirect USB 2.0	Romexis
Schick 33	Dentsply Sirona	CMOS	12	Indirect USB 2.0	Schick CDR Software
XDR	XDR Radiology	CMOS	12	Direct USB 2.0	XDR Software

[*] CMOS: Complementary metal-oxide semiconductor. [†] USB: Universal Serial Bus.

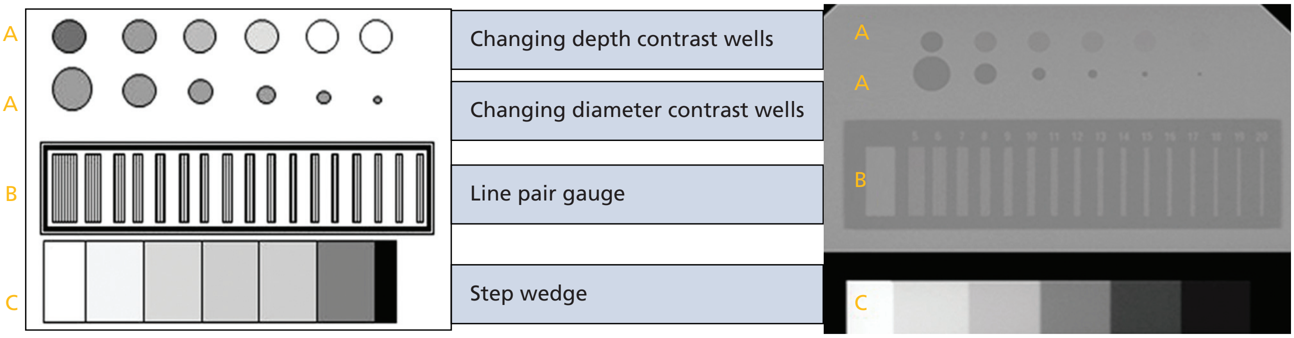

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Figure 2. Schematic representation of Digital Dental Quality Assurance test components and accompanying radiograph. Image quality parameters: low-contrast detectability (**A**), spatial resolution (**B**), and dynamic range (**C**).

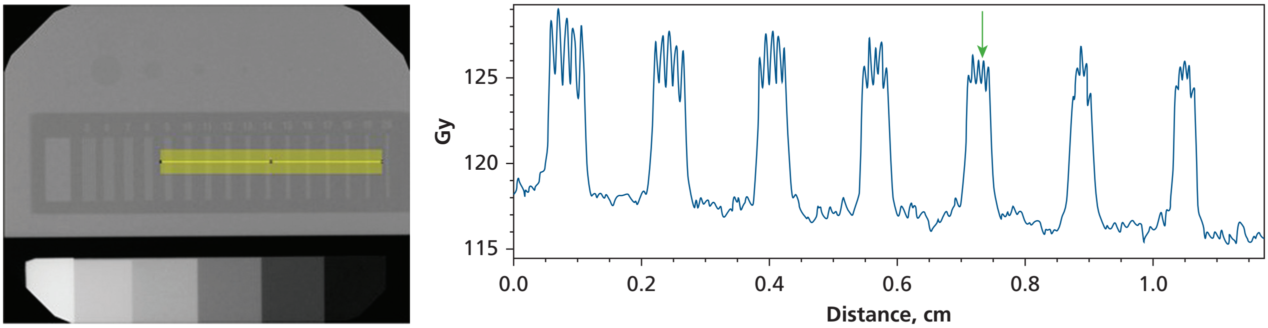

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Figure 3. Analysis of spatial resolution pattern. Arrow: spatial resolution of 13 line pairs/mm.

image as 5 distinct peaks and 4 valleys (Figure 3). We scored the highest line pair segment with all 5 peaks clearly visible as the spatial resolution.

We determined the dynamic range and latitude via analysis of the step wedge. We assessed the dynamic range by means of ensuring that all 7 steps of the step wedge were visible as distinct contrasts, as shown by 7 horizontal steps by the ImageJ software (Figure 4). The latitude of each imaging system was determined by the range of exposures for each system capable of displaying the full dynamic range as 7 distinct, horizontal steps of the step-wedge pattern.

We identified the optimal exposure as the lowest exposure time that provided an image with the full latitude and the highest visualization of contrast wells and measured spatial resolution. When we determined the optimal exposure for each imaging system, we compared it with the published DRL for intraoral radiographic examinations in National Council of Radiation Protection and Measurements report 172.[13]

Endodontic phantom

To assess the clinical impact of exposure optimization, we designed and fabricated a phantom of relevance to endodontic imaging (Figure 5). The endodontic phantom simulated a clinical situation that allowed evaluation of exposure optimization on a diagnostic task. The endodontic phantom consists of a size no. 6 0.02 K-file positioned at the apex of an endodontically prepared palatal root of a maxillary first molar. Placement of the size no. 6 K-file at the apex was confirmed using a scanning electron microscope. Size 6 is the smallest endodontic K-file and most difficult to visualize radiographically at the apex. The K-file was then affixed in place with clear acrylic resin injected into the palatal canal and pulp chamber (Figure 5). The prepared molar was then fixed in place within a 2.5-cm thickness of clear polymethyl methacrylate plastic base to simulate bone. The palatal root vertically was fixed in an upright position and parallel to the imaging surface of the intraoral image receptor during image acquisition. A slot was prepared in the acrylic base to facilitate positioning the image receptor parallel to the palatal root.

We obtained a high-resolution cone-beam computed tomographic scan of the endodontic phantom with the Accuitomo 170 computed tomographic scanner (4 cm × 4 cm field of view) print & web 4C/FPO

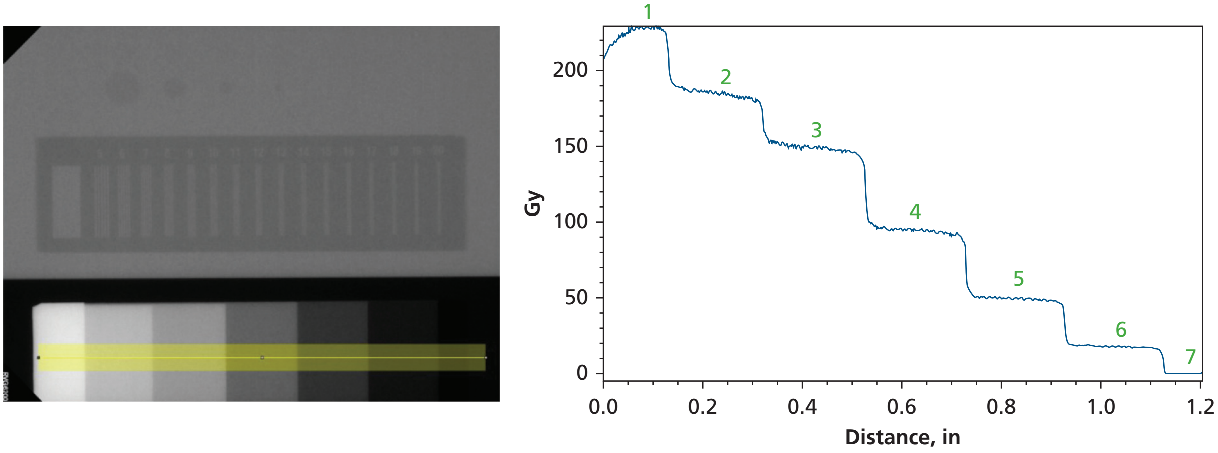

Figure 4. Analysis of step-wedge pattern for dynamic range (full exposure latitude).

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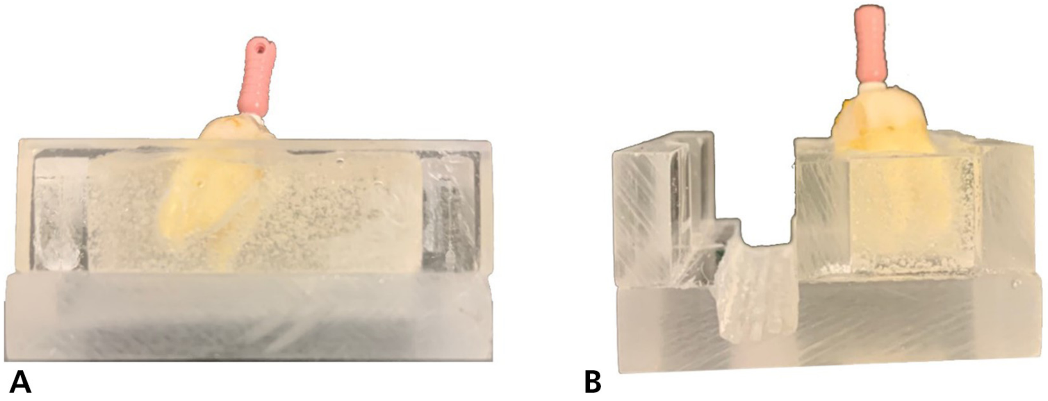

Figure 5. Endodontic phantom. **A**. The vertical and parallel positioning of the palatal root relative to the image receptor. **B**. Side view showing the slot for stanadardizing the placement of the various image detectors within the endodontic phantom.

(J. Morita USA) to verify the vertical positioning of the size no. 6 K-file within the palatal root and parallel relationship to the intraoral image receptor.

We obtained radiographs of the endodontic phantom using 3 different exposure times: at the optimum exposure time as determined with the DDQA phantom, at 1 incremental exposure setting above, and at 1 below the optimum exposure time.

The shortest distance between the tip of the endodontic file from the palatal root apex was measured using ImageJ by 1 observer (A.B.B.), who made 4 independent measurements.

Statistical analysis

We entered data into Prism (Graphpad) and used them to generate summary statistics. We analyzed differences in optimal exposure times and the measured distance from file tip to root apex using analysis of variance ($P < .0001$).

RESULTS

Optimal exposure time and image quality

The determined optimal exposure times varied among the 7 direct-capture digital systems, with a range of 0.1 s through 0.32 s (Table 2). All sensors were capable of providing the full range of image densities of the step wedge. However, the sensors varied greatly in the optimal exposure setting. The highest optimal exposure setting (LED Tuxedo) was more than 3-fold that of the lowest optimal exposure sensor (Planmeca ProSensor HD). For all sensors, exposures made at the optimal exposure times were below the DRL of 1.6 mGy for intraoral radiographic examinations and yielded images

Table 2. Optimum exposure for digital intraoral systems.[*]

DIGITAL IMAGING SYSTEM[†]	OPTIMAL EXPOSURE TIME, s	OPTIMAL EXPOSURE, mGy	CONTRAST PERCEPTIBILITY		PERCEPTIBLE SPATIAL RESOLUTION, LINE PAIR/mm	LATITUDE OF SENSOR, THRESHOLD	
			Changing Depth Wells, No.	Changing Diameter Wells, No.		Lower	Higher
Carestream 6200	0.25	0.83	4	5	15	0.032	0.32
Dexis Platinum	0.16	0.53	4	5	13	0.012	0.8
Gendex GXS-700	0.16	0.53	3	5	13	0.010	0.8
LED Tuxedo	0.32	1.06	4	5	14	0.012	0.8
Planmeca ProSensor HD	0.1	0.33	4	5	10	0.010	0.8
Schick 33	0.12	0.42	4	5	14	0.016	0.16
XDR	0.25	0.83	4	5	14	0.025	0.8

[*] Images were obtianed at 63 kVp and 6 mA, source-to-detector distance of 30 cm, and varying optimum exposure times. † Manufacturers are listed in Table 1.

Table 3. Measurement of file tip location from radiographic apex.[*]

SENSOR[†]	MEASURED DISTANCE OF FILE TIP TO APEX, MM, MEAN (SD) (%)[‡]		
	1 Step Below Optimal Exposure	Optimal Exposure	1 Step Above Optimal Exposure
Carestream 6200	0.169 (0.013) (208)	0.082 (0.003) (100)	0.169 (0.004) (207)
Dexis Platinum	0.216 (0.009) (202)	0.107 (0.007) (100)	0.263 (0.009) (246)
Gendex GSX-700	0.179 (0.008) (107)	0.167 (0.004) (100)	0.228 (0.01) (136)
LED Tuxedo	0.209 (0.004) (134)	0.156 (0.004) (100)	0.228 (0.004) (147)
Planmeca ProSensor	0.121 (0.004) (131)	0.093 (0.004) (100)	0.228 (0.004) (245)
Schick 33	0.158 (0.006) (174)	0.091 (0.008) (100)	0.203 (0.011) (223)
XDR	0.133 (0.008) (150)	0.089 (0.005) (100)	0.108 (0.005) (122)

[*] Scanning electron microscopic and cone-beam computed tomographic imaging confirmed the location of the file tip at the physical root apex. To quantify differences in measurement made with different exposure times, the data were normalized to the distances measured on images made at the optimal exposure. † Manufacturers are listed in Table 1. ‡ Each imaging system was compared to itself by measuring the distance between the file tip and the radiographic apex at the optimal exposure and then at 1 increment above and below. The first number listed is the mean distance of the file tip to radiographic apex. The second number indicates the standard deviation of the mean values. The third number is the percentage of deviation from the optimal exposure value at 1 increment above and below the optimal for each imaging system.

with high contrast perceptibility, providing visualization of 3 through 5 contrast wells. Images obtained at the optimal exposure time differed in their spatial resolution, depending on vendor, and ranged from 10 line pairs/mm to 15 line pairs/mm. There was no association between the magnitude of the optimal exposure and the image quality parameters measured.

Endodontic phantom evaluation

The perceived location of the file tip from the apex varied in the images from the 7 sensors (Table 3, $P < .0001$). This perceived distance changed when images were obtianed at exposure times other than the optimal setting. Changing the exposure by 1 exposure step resulted in an almost 2-fold change in the perceived distance between the file tip and root apex.

DISCUSSION

Despite the many similarities in the design and construct of digital intraoral sensors, there are perceptible differences in their image quality. Our study confirms findings from previous studies that found significant differences in the performance of individual digital imaging systems.[2,9,10,12] The optimal exposure time for each sensor model varied, emphasizing the need to optimize exposure settings for each sensor system. This confirms the premise of Standard 1094, which is that the intraoral radiographic system includes not only the physical sensor but also the vendor-specific software and the computer display used to present the image. When any of these elements is changed, the team must confirm continued validity of previously optimized settings.

All 7 sensor systems used in our study provided the full range of radiodensities of the step wedge (Table 2). However, their latitude—the exposure range over which the densities were perceptible as distinct steps—varied. One sensor (Schick 33) was saturated with photons with an exposure time of 0.16 s, slightly higher than its optimal exposure time of 0.12 s. A second sensor (Carestream 6200) was saturated with photons at an exposure of 0.32 s, relative to its optimal exposure time of 0.12 s. For the other 5 sensors, this saturation was reached only at an exposure time of 0.8 s. Sensors with a wide latitude allow the user to make a diagnostic image over a broad range of exposures. The user may obtain radiographs at exposures much higher than the optimal setting but subsequently adjust the image histogram to visually enhance the required details, leading to unnecessary radiation exposure of patients. The establishment of optimized exposure settings, guided by image quality as outlined in Standard 1094, will help prevent such unnecessary overexposure.

Even when radiographs are obtained at the optimal exposure, there are differences in the quality of the image produced by different sensor systems. Likely, this is due to differences in the software components of the imaging system and represent proprietary elements of each vendor, because there are many similarities in construction as described earlier. Dentists, as consumers, must be aware of this data so that they can select the product that best fits their imaging needs.

To determine the clinical impact of image optimization, we fabricated an endodontic phantom to allow assessment of the relation of an endodontic instrument and the root apex. Measurements of the distance of the file tip to the apex differed between images made at optimal exposure settings and with exposure times other than the optimal exposure. Even a single incremental exposure above or below the optimal exposure setting resulted in a change in the perception of the endodontic instrument, and this underscores the clinical relevance of optimizing exposure charts for intraoral imaging procedures. Technique charts need to consider the entire system used, including the sensor, software, and display system, and, therefore, manufacturer-supplied technique charts require validation within the practitioner's own combination of sensor, software, and display monitor.

The proper working length and location of the endodontic file relative to the apex are key factors in endodontic treatment of a tooth. The proper working length ensures that the entire canal is prepared and treated for a proper apical seal and obturation. Success or failure of an endodontic treatment may hinge on whether the entire canal has been cleaned and shaped properly for the apical seal. Inaccuracies in measuring the distance between the radiographic apex and tip of the endodontic file may result in incomplete cleaning and shaping and lack of apical seal, leaving residual infectious material behind, and this may result in endodontic failure.

Although there is a widely held belief that digital intraoral radiographs may be optimized after image acquisition by means of adjusting brightness and contrast or the use of postprocessing software algorithms, the study by Kal and colleagues[14] indicates otherwise. The actual length of the endodontic file could not be established using various digital processing algorithms after the radiographs were obtained. With all 360 images analyzed, the endodontic file appeared shorter than the actual file length when measured from the radiographic apex to the endodontic stopper despite the application of 5 different postprocessing software algorithms.

Image optimization is a concept that often is discussed in dental radiographic literature, but the method to achieve it is often unclear or vague. For example, the International Atomic Energy Agency describes image optimization as follows: "Optimization-radiographic quality. If a patient is exposed to X-rays for the purpose of producing a radiograph, but the resulting image is not of adequate quality for clinical use, then the patient has been put at risk for no benefit. Ensuring adequate quality is, therefore, a fundamental part of radiation protection."[15] The words adequate quality are vague and imprecise and fail to offer a meaningful guidance to achieve image optimization. In our study, images obtained at and then 1 increment away from the optimal exposure were of "adequate quality" such that the endodontic file tip and radiographic apex were visible to allow a measurement. However, measurements made on images at nonoptimal exposures were significantly inaccurate, relative to measurements made on images made with optimal exposure. Thus, visual observation of adequate quality fails to achieve the stated goal of image optimization.

Silverstrim and colleagues[16] have proposed an alternative approach to image optimization, to balance image quality and radiation dose using a Monte Carlo simulation method. However, this method is much too difficult and cumbersome for a dental practice to implement. Another shortcoming is that this method recommends an exposure setting at 90 kVp to improve contrast between teeth and bone, which exceeds the maximum kV on most contemporary intraoral radiograph units. Furthermore, this study failed to consider the need to evaluate periodontal status such as crestal gingiva tissue height and lamina dura and other factors used to assess periodontal health.

Another study comparing traditional and digital radiographs found that film-based radiographs were more accurate in determining the working length of the file in conjunction with an apex locator.[17] Similarly, another study found that the perceived clarity of fine endodontic files and periapical lesions was significantly less with phosphor-plate digital images than with traditional radiographs.[18] Neither of these studies used an image optimization process during the acquisition of the digital radiographs as we did in our study.

One limitation of our study was the number of observers who scored the images. Another limitation in this study was that only a single diagnostic task was assessed: the identification of the tip of an endodontic instrument. Thus, these results should be validated for other diagnostic tasks including assessment for caries, periodontal disease, and apical periodontal inflammation. Nevertheless, to our knowledge, our study is the first demonstration of a clinically relevant radiologic assessment that may be affected by image optimization. Future studies should evaluate whether digital enhancement tools could compensate for the decreased quality of images that are not obtained with optimal exposure settings.

CONCLUSION

The procedures outlined in Standard 1094 allow the dental team to optimize exposure settings on the basis of the imaging system used in their clinic. The results of our study show direct clinical relevance of image optimization, specifically for endodontic instrumentation, and support our hypothesis that image optimization positively affects diagnostic assessment. ■

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Disclosures. Dr. Mah is the president of Dental Imaging Consultants, which holds a patent for the Digital Dental Quality Assurance phantom and is an authorized distributor for Raysafe Unfors products. Drs. Barrineau and Mallya did not report any disclosures.

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