Digital and Advanced Imaging in Endodontics: A Review

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Abstract
This review provides an overview of digital radiography as it exists, including advanced imaging such as computed tomography (CT), cone beam volumetric imaging, and micro-CT as relevant to the practice of endodontics. An evidence-based approach to adoption of different imaging technologies is included to assist the practitioner with the selection process of imaging modalities. Commonly used imaging terminology is introduced, as well as the advantages and disadvantages of image processing. New image reconstruction techniques have been introduced that provide information three-dimensionally to the clinician for routine endodontic and surgical treatment planning. The age of three-dimensional imaging and image processing is here. Limitations and advantages of newly introduced imaging modalities are discussed briefly. *(J Endod 2007; 33:1–6)*

Key Words
Computed tomography, digital, imaging, processing, radiography, reconstruction, scan

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Recent improvements in digital radiographic imaging systems have introduced many potential benefits to endodontic practice. Instantaneous generation of high-resolution digital images; manipulation or processing of the captured image for enhanced diagnostic performance; lack of need to reexpose patients for potential retakes; lower dose compared with D-speed film with round collimation; ease of archiving, transmission, and long-distance consultation; lower turnaround times; reduction in time between exposure and image interpretation; and digital documentation of patient records are some of the advantages (1, 2) of digital radiography. The quality of the image is probably of the utmost significance in endodontics, as it facilitates accurate interpretation of root and canal morphology, and particularly the determination of radiographic canal length, as well as the postoperative and long-term evaluation of the outcome of endodontic treatment (3).

Various digital imaging modalities are available today. Image acquisition is facilitated with the use of several technologies that incorporate sensors using solid-state technology, such as charge-coupled device (CCD), complementary metal oxide semiconductor (CMOS), or photostimulable phosphor (PSP) technology, which is sometimes referred to as a semi-direct or indirect acquisition modality, and truly indirect methods, such as the use of flatbed scanners or CCD/CMOS-based video cameras to digitize radiographs. Such cameras could be mounted on a stand and images captured using a frame-grabber assembly.

An Overview of Different Modalities

The first-generation intraoral solid-state sensors used CCD technology. Numerous drawbacks existed with these sensors. Currently available systems have worked around these drawbacks, which included, among others, a relatively smaller active area, bulkiness, and lower absorption and conversion efficiency of incident radiation. These solid-state sensors use an array of radiation-sensitive or light-sensitive elements that quantify the intensity of the incident radiation (X-ray or light) by generating a proportional electric charge that is then read as a voltage. These readings are then transferred to an analog-to-digital converter in the frame-grabber assembly. Once digitized, these signals are converted into analog signals for viewing on the monitor. To enhance the efficiency of the sensor and reduce the radiation dose, a scintillation layer, such as a phosphor material, is added to the surface of the detector array to facilitate conversion of incident X-rays to light. This layer is painted onto the CCD chip or laid over the CCD with fiberoptic coupling. Sensor sizes vary and are now available in sizes comparable to those of # 0, 1, and 2 intraoral film, with active areas approaching similar dimensions. Instantaneous image generation is possible with solid-state sensors.

CMOS-based sensors are also used for similar image acquisition. Recently developed additions include an active pixel sensor (APS) component. The sensor has an active transistor at each element location. It uses less power and is less expensive to manufacture, and the circuitry is built into the sensor. CMOS semiconductors are manufactured for a variety of other solid-state devices. Disadvantages include a more fixed pattern noise and smaller active area owing to integrated circuitry. Wired and wireless sensors are also available. Comparison of the objective, task-based, image quality of the CMOS with earlier generation CCD-based detectors showed no difference in diagnostic capabilities (4). This is noteworthy from a diagnostic perspective.

Recent advances in sensor technology have resulted in the generation of high-resolution images. Spatial resolution is usually expressed in terms of line pairs per millimeter (lp/mm). Film has a resolution of 16 lp/mm, which increases to about 20 to 24 lp/mm with magnification. Hence, magnification is advised for all film-based radiographs. Newer generations of solid-state sensors have similar or even slightly higher spatial resolution. However, selection of sensors should not be made based on just spatial resolution; the diagnostic task assumes importance here. Slight differences in spatial resolution do not cause an appreciable difference in diagnostic efficiency. Likewise, dynamic range is another significant property of sensors. It refers to the range of exposures that the sensor would tolerate and still produce a diagnostically acceptable image.

PSP sensors were introduced in the mid-1980s as Fuji computed radiography (5), although the physics of phosphorescence and latent image formation were known for a long time (4). Intraoral, panoramic, and cephalometric size sensors have since become available. PSP imaging is also referred to as computed radiography (CR), photostimulable phosphor radiography (PPR), and storage phosphor radiography. The devices are wireless, thin sensors that record a latent image upon exposure to radiation. The images can be erased by exposing the sensor to intense white light, making the sensor reusable. Associated problems unique to this technology include the potential for physical damage sustained by the plates being scratched and incomplete erasure of previous images, resulting in ghost images. Sensors are relatively inexpensive. The dynamic range is significantly higher than that of solid-state sensors; resolution is slightly less. However, for most diagnostic tasks in dentistry, PSP sensors have been shown to be as good as CCD/CMOS sensors. Studies specific to endodontics will be discussed later.

Image Characteristics: Overview of Terminology

Contrast and Spatial Resolution

Contrast resolution is defined as the ability to differentiate between areas on the image that differ in density. Most diagnostic tasks require a high contrast resolution. Spatial resolution is the ability of the system to display two discrete objects that are very close together as two distinct entities. Contrast and spatial resolution are related to the radiation dose absorbed by the sensor (quantum mottle) in addition to other factors. Computed tomography (CT) has the highest contrast resolution but spatial resolution is inferior to that of intraoral film. Cone beam CT (CBCT) or volumetric tomography (CBVT) have relatively higher spatial resolution than medical-grade CT; however, the scatter is higher with CBCT.

Image Processing

Image processing enables extraction of signals of diagnostic interest from a radiograph. However, it cannot produce information that is missing. The digital radiograph has to be of optimal image quality and acquired using optimal exposure parameters. Numerous image-processing algorithms exist for different diagnostic tasks. Inappropriate processing of signals has been shown to degrade image quality and render the radiograph nondiagnostic (6). A thorough understanding of the physical principles of each processing technique is central to teasing out the desired information using that technique. Enhancements done on images must be task-specific. There are no set parameters that would work for all diagnostic tasks. Therefore, pilot studies are advocated to optimize image quality.

Contrast Enhancement

Studies using contrast enhancement have found it to be useful for specific diagnostic tasks. Most of these studies were carried out for nonendodontic diagnostic tasks. However, one study reported that Visualix-2 images (7) (Gendex Dental Systems, Lake Zurich, IL) that were contrast enhanced outperformed film for evaluation of the size of periapical lesions.

Image Compression

Images can be reduced in size for storage or transmission purposes. Compression modes, otherwise known as image coding, are either lossy (irreversible) or lossless (reversible), depending on the diagnostic task at hand and need for future retrieval (8). Image archiving and communication are integral components of digital radiology and teleradiology. Most insurance carriers accept electronic images. The results of a study to evaluate lossy compression for endodontic pretreatment digital radiographs suggest that high compression ratios can have a severe impact on the diagnostic quality of digital radiographs for the detection of periapical lesions (9). Analysis of the effect of a reduction in size of digital images on diagnostic outcome using a series of 100 Visualix III (Gendex Dental Systems) images using size 10 and 15 endodontic files on maxillary and mandibular premolars revealed that reduction in size may cause less detectability as well as loss of diagnostic information (10). Radiographs processed to correct for attenuation differences and visual perception have been demonstrated to facilitate determination of the length of thin endodontic files. Such processed radiographs are comparable with radiographs processed with the default processing employed by image acquisition software (Sidexis, Sirona Dental Systems, Charlotte, NC) (11).

Images are ideally saved in tagged image file (.tif) format to avoid loss of information. Alternatively, they could be saved in Digital Imaging and Communications in Medicine (DICOM) format. DICOM was developed as a universal standard for medical image encoding for transmission and archival purposes so that images generated by different units using different acquisition and processing software could be read without loss of information in any other viewing or processing software. The American Dental Association (ADA) has recently developed a DICOM standard for use in dentistry. DICOM-conforming software is currently available that facilitates interoperability of multiple imaging systems (http://www.ada.org/prof/resources/positions/standards/informatics.asp).

The very first system that was introduced in digital radiography in dentistry was Radiovisiography (RVG, formerly Trex-trophy Radiology Inc., Marietta, GA) by Trophy in France in 1987. It used a CCD-based sensor, with images being displayed on a television monitor. One of the earliest studies using the system was a comparative evaluation of imaging of root canals using conventional film and RVG. No differences were found in the length of canals visible (13). There are many studies comparing various systems with regard to working length determination (11–26) and accuracy of detection of periapical lesions (27–32). Most of these studies used objective criteria (measurements) to test the diagnostic quality of images produced by various techniques. However, evaluation of image quality as a function of clarity is a subjective judgment that comprises both the technical qualities of the image as well as the experience, skill, and visual perception of the viewer.

Some of the earlier systems had clear disadvantages. Images from CCD and PSP sensors did not have the spatial resolution offered by intraoral film, which prevented their widespread adoption by the dental community. Unlike medical radiology, the resolution requirements are very high for dentistry. At that time, significant limitations existed in sensor technology. Therefore, it was thought that intraoral sensor systems alone were unlikely to improve image quality for endodontic tasks (33). However, recent improvements and continuing development of newer sensor technology have facilitated just that. In addition, images render themselves to digital enhancement processes owing to their bit depth and dynamic range. Bit depth indicates the shades of gray that are recorded in an image. Earlier systems produced 8-bit images with 256 shades of gray. Newer ones are capable of 12-bit and 16-bit image generation with 4,096 and 65,536 shades of gray, respectively; the human eye can see only about 32 shades of gray at any one point in time.

Capturing all available gray-level information ensures that the shades of gray are available for processing when certain signals of known characteristics need to be teased out. Loss of this information in an 8-bit image prevents visualization of such diagnostic signals, as they simply do not exist in the captured image. Image processing can be put to use only if there is raw information stored digitally in the raw image.

Working-Length Determination

Numerous studies have evaluated the performance of film-based and digital radiographs for determination of working length. A study comparing the segmental measurement tool in the Schick Technologies CDR digital system (Schick Technologies, Inc., Long Island City, NY) with conventional film radiography for preoperative working-length determination showed the mean measurements for both modalities were not significantly different from the gold standard. The modality most closely approaching the gold standard was conventional film (13). The efficacy of RVG, PSP, and conventional radiography for root canal length measurement was evaluated, and results showed that the highest accuracy of measurement was recorded with conventional radiographs. The agreement between the two digital systems was best with a size 15 file using 0 degrees of projection geometry (66.7%) (14). Comparison of digital images with film-based radiographs for perceived clarity of small endodontic file tips at two different working lengths, as well as for the visualization of periapical bone lesions where present, revealed that perceived clarity of fine endodontic files and periapical lesions was significantly less with phosphor plate-based digital images than with conventional radiographs (15). Mentes and Gencoglu compared measurement of the length of curved canals by direct digital and conventional radiography and concluded that the image quality of the former had improved to the point where it could be used for measuring curved canals, with accuracy comparable to that of conventional radiographs (16). However, further work remains to be done to optimize image quality. Another study comparing the accuracy of file length measurements made on calibrated and uncalibrated direct digital images showed that the calibrated measurements were more accurate than the uncalibrated measurements (17). The purpose of this study was to evaluate measurements of endodontic files of known length and diameter using a density profile plot analysis of digital images. This study demonstrated that the density profile plot analysis might be a useful adjunct for the measurement of endodontic file lengths on a digital image (18). Comparison of digital dental X-ray systems with self-developing film and manual processing for endodontic file length determination showed that the measurement error was significantly less for the digital images than for the film-based images. It is likely that these statistical differences may not be of great clinical significance because the digital images could be measured in increments <0.25 mm (19). A study comparing direct (using endodontic ruler and calipers) and indirect measurement (conventional radiograph with calipers and digital radiographic measurement system) of root canal length showed no statistically significant differences between the direct and indirect methods. Changes in vertical angulation were employed for the indirect methods (00, 150, and 300). No significant differences were found between results for the two indirect methods versus the standard method except for the 300 angulation, which resulted in foreshortening of about 1.5 mm ($p < 0.05$) (20). Comparison of two PSP systems versus radiographic film for difference in interpretation of the position of endodontic file tips showed a smaller difference between file tip and root apex found with digital imaging, suggesting that this technique is more accurate to assess trial file length. This imaging modality for assessing file positions during root canal treatment may be beneficial to the practitioner (21). Digital images produced by digital systems can be magnified, depending on monitor resolution and compression modes. Differences in size may introduce difficulties when estimating distances (e.g. during endodontic treatment) (3). The effect of dose reduction on the image quality with automatic grayscale adjustment using two digital sensor systems, CCD-based Sidexis (Sirona Dental Systems) and PSP-based Digora (Soredex, Milwaukee, WI), was tested. With the systems tested, a dose reduction of approximately 95% compared with Ektaspeed films (Eastman Kodak, Rochester, NY) is possible to determine the lengths of a premolar root, and 25 and 20 size files. For thinner objects a dose reduction is questionable (22). The quality of Digora (Soredex) with respect to the visibility of endodontic files and root apices at different exposures showed that the Digora intraoral image plate system (Soredex) provided reliable endodontic measurements even at very low exposures (23). This can be attributed to the increased dynamic range of PSP sensors. CCD-based RVG (formerly Trex-trophy Radiology Inc.) was compared clinically to conventional D-speed and E-speed (Eastman Kodak) film-based images viewed with $\times 2$ magnification to evaluate using the mesiobuccal root of maxillary molars of 22 patients. D-speed film-based radiographs (Eastman Kodak) were statistically superior to RVG images (formerly Trex-trophy Radiology Inc.), whereas E-speed film images were comparable to RVG (24). However, recent upgrades in sensor technology enable acquisition of high-resolution images. A study comparing RVG (formerly Trex-trophy Radiology Inc.) with conventional radiography showed no significant difference in the ability of endodontists to make accurate file length adjustments using the two systems. In this study, it was found that accurate file length adjustments can be made from an image two times larger than the actual tooth, that RVG is not significantly better than conventional radiography, and that if both methods are available, RVG was preferred because of the significant reduction in radiation dose (25). Sanderink et al. (26) concluded that RVG units and Sens-A-Ray (AFP Imaging Corp., Elmsford, NY) render comparable results to conventional radiography for determining root canal length with size 15 files. All sensor systems were unacceptably inferior to film images when size 10 files were used (26). However, the study used sensors belonging to an earlier generation, with significant resolution limitations. In yet another study, measurement accuracy was compared among EktaSpeed film and two CCD-based systems: RVG-S and FlashDent (Villa Sistemi Medicali, Italy), using tools in the proprietary software of the digital systems in comparison with conventional measurement on film. No significant differences were noted (34), indicating that digital systems performed comparably with film.

Diagnosis and Healing

Image processing has been shown to improve diagnostic quality. However, optimal processing parameters have to be employed based on the diagnostic task. Evaluation of the efficacy of digital subtraction radiography using a direct digital imaging system (RVG-S, formerly Trex-trophy Radiology Inc.) has also been carried out. In a prospective study of endodontically treated teeth using standardized radiographs, it was found that pixel values at the regions of interest positioned on the periapical lesion increased after the endodontic treatment, and this change continued during the observation period up to 545 days, indicating continued osseous healing (27). Subtraction using direct digital radiography is thus a useful tool in evaluating the healing process in endodontic treatments. Evaluation of the effect of root canal treatment on periapical lesions by conventional and subtracted digital radiographic images of clinical cases showed that a significantly better observer agreement was achieved by digital subtraction radiography (28). Another study to evaluate digital subtraction radiography to monitor progress of chronic apical periodontitis using preoperative, postoperative, control, and recall radiographs, which were contrast-enhanced and subjected to pseudocoloring, indicated that even changes occurring over a short period of time could be detected (29). Changes to the periapical tissue structure were easily detectable by using the above-mentioned methodology, even during short time intervals (29). Direct digital radiography (DDR) and telephonically transmitted images versus conventional radiography in the detection of induced periapical lesions showed that there were no statistically significant differences in diagnostic accuracy of archived digital images, transmitted images, and conventional film images (30).

The advantages of appropriate image processing were again evident in another study that compared the efficacy of conventional and digital radiographic methods in diagnosing simulated external root resorption defects. It was easier to detect these lesions on digital radiographs (31). Image clarity thus plays an important role in facilitating accurate diagnosis. Films and PSP-based systems were evaluated in a study that compared the subjective image clarity of two different-speed films and Digora PSP images (Soredex), indicating that the perceived image quality of the enhanced Digora images was significantly superior to all other images for the evaluation of root fillings, followed by EktaSpeed film. F-speed and unprocessed Digora images performed comparably (32).

Three-Dimensional Imaging

A few studies on three-dimensional (3D) imaging modalities that are pertinent to endodontics have been reported. CT used to evaluate root canals prepared by nickel-titanium (NiTi) hand and stainless steel hand endodontic instruments showed that the system used in this study provided a repeatable, noninvasive method of evaluating certain aspects of endodontic instrumentation, such as canal transportation, dentin removal, and final canal preparation (35). Another study using 50 patients to compare diagnostic information gathered from conventional two-dimensional (2D) dental radiography and high-resolution CT with regard to the detection of endodontic lesions and its relation to important neighboring anatomic structures such as the mandibular canal concluded that the use of CT provides additional, 3D information not available from conventional 2D radiographs for treatment planning in apical surgery of mandibular premolars and molars (36). For instance, difficulty in localization of the inferior alveolar canals on conventional radiographs may be an indication for 3D imaging for endodontic surgical treatment planning. Visibility of the canal on extraoral radiographs does not permit localization of the canal in 3D. However, periradicular lesions can be effectively detected and localized in relation to critical anatomic structures such as the mandibular canal on CT (36). Nonetheless, inferior alveolar canals cannot always be traced fully on CT studies. If canal cortication is lost, or if thin slices are being evaluated, canal outlines may be difficult to trace, owing to loss of contrast. In such instances, slice thickness could be increased or volumetric 3D renderings could be done to try to visualize the canal. Sometimes, none of these techniques yield results.

Photogrammetry has also been employed to try to accurately and reproducibly chart canal configuration (37). Two views (mesiodistal and buccolingual) of digitized images of extracted teeth were used to correct for geometric distortion (37). Each of these axis pairs was used to generate a 3D polynomial function of the actual root canal. In another study, CT (38) was used to examine root anatomy in three cases of paramolar tubercles. The images clearly showed the structure of the paramolar tubercles, including their root canal morphology. The root of the paramolar tubercle was united with the distobuccal root in each case. Canals were observed in all tubercles and were connected with the canals in distobuccal roots at various levels. In one case, the imaging information was helpful for endodontic treatment. Fractal analysis was used in evaluating correlation of external and internal macromorphology of the roots. It was shown that 3D volumes may be of use in preclinical training in endodontic procedures (39).

Micro-CT has also been evaluated in endodontic imaging (40–43). Comparison of the effects of biomechanical preparation on canal volume on reconstructed root canals in extracted teeth using micro-CT data was shown to assist with characterization of morphological changes associated with these techniques (40). Peters et al. (41) used the micro-CT to evaluate the relative performance of ProTaper NiTi instruments (Dentsply Maillefer, Tulsa, OK) in shaping root canals of varying preoperative canal geometry. A study to examine the potential and accuracy of micro-CT for imaging of filled root canals showed it to be a highly accurate and nondestructive method for the evaluation of root canal fillings and their constituents. Qualitative and quantitative correlation between histological and micro-CT examination of root canal fillings was high (42, 44). However, note that micro-CT remains a research tool and cannot be employed for human imaging in vivo.

The possibility of using low-dose, low-cost local CT to obtain anatomic information to plan periradicular surgery via the vestibular approach was explored successfully (42). It was determined that the mean root apex-vestibular cortex distance was 9.73 mm. In 25% of cases, the maxillary sinus demonstrated alveolar extensions into the area between buccal and palatal roots. CT may play an important role in optimizing palatal root-end surgery through vestibular access, with regard to precision and preventing complications, with relatively low biological and economic costs, also possibly contributing to the affirmation of this new surgical procedure (42). Ebihara et al. incorporated CT with 3D reconstruction in the diagnosis and monitoring of a case of Garre's osteomyelitis managed by root canal treatment of a mandibular second molar (45).

Volumetric CT (VCT) or CBCT, a relatively new diagnostic imaging modality, has been used in endodontic imaging recently. This modality uses a cone beam instead of a fan-shaped beam as in medical-grade CT, acquiring images of the entire volume. It offers relatively high resolution, isotropic images in comparison with medical-grade CT images, for effective evaluation of root canal morphology. Even though resolution is not as high as that of conventional radiographs, the availability of 3D information and a relatively higher resolution and a significantly lower dose than medical-grade CT makes CBCT the imaging modality of choice in challenging situations demanding localization and characterization of root canals. Potential applications in endodontics include diagnosis and evaluation of most aspects of endodontic treatment, such as determination of the configuration and length of root canal, presence of accessory canals, and the like (44, 46). VCT was used to visualize vertical root fractures in extracted teeth. Vertical root fractures were successfully detected at a spatial resolution of 140 μm (47). However, only a limited number of units provide such high resolution. Continued improvement of sensor technology, including the use of flat-panel detectors in these units, has resulted in enhanced resolution. Voxel dimensions are smaller in these units. Another recent study attempted to study the course of the inferior alveolar canal within the alveolar process using panoramic radiography and CT, with ground truth determined by cadaveric dissection (48). CT was found to be accurate. Such information is crucial to treatment planning and also during the course of endodontic procedures.

Tuned aperture computed tomography (TACT) has also been studied in detail for its applications in endodontics (49–55). TACT is a relatively new 3D imaging modality that uses multiple conventional 2D images to reconstruct a 3D volume that could then be examined in incremental slices in static or dynamic modes. The significant advantages of TACT are that the doses are relatively low, no expensive equipment is required, image acquisition is relatively simple, artifacts associated with CT such as starburst patterns seen with metallic restorations do not exist, resolution is as good as conventional 2D radiographs, and patient motion is tolerated. It was noted that root canals were easier to detect on TACT images than on conventional radiographs (50). No differences in detection rates of the second mesiobuccal canals in maxillary molars were noted in another study comparing TACT to conventional radiographs, both digital and film-based, using the parallax method (51). However, this study used simulated bone. Extrapolation to the clinical scenario is difficult. Other studies confirmed the superior diagnostic efficacy of TACT in the detection of induced oblique or vertical radicular fractures (VRFs) (52), and VRFs in nonrestored maxillary teeth that sustained trauma (53). Image processing seemed to play a crucial role, in that images subjected to repeated iterative restoration in the TACT workbench software resulted in better signal detection (54, 55). TACT thus seems to offer advantages of conventional radiography in terms of resolution of resulting slices, as well as that of tomography, in that information in 3D is available for interactive evaluation. These studies used cadaver specimens, closely approximating the clinical scenario (52–55). However, the fractures were induced, and more clinical studies may be in order.

Conclusions

Digital radiography has several advantages and has become an indispensable diagnostic tool for many dentists in daily practice. Once the digital image appears on the monitor, the dental X-ray software allows image enhancement that should be used with caution, based on the diagnostic task. Inappropriate use of enhancement has been shown to adversely affect diagnosis. If digital radiographs are exported using various software packages created for graphic design and image manipulation, digital information can be altered, added, or removed. The DICOM standard has been accepted as the universal standard for image transmission and archiving. DICOM ensures that all images are readable in any viewing software without loss of fidelity or diagnostic information. Image enhancement features of digital radiography allow mishandling of images, leading to potential abuse. Recently published studies illustrate the potential for fraudulent use of digital radiography (56).

There is a dearth of studies relating to diagnostic performance of the numerous sensors that are currently available in the market. Slight to moderate differences in resolution exist. With rapid advancement in sensor technology and frequent software upgrades occurring on a regular basis, selection of one system over the other for a specific diagnostic task seems to be challenging. In a recent review of the most commonly used solid-state sensors, Farman and Farman (57) reestablish the fact that most perform comparably with film. The Kodak 6000 CMOS-based sensor and the RVG-ui (CCD) displayed the highest spatial resolution of 20 line pairs/mm (same as Kodak F-speed Insight film), whereas the Visualix HDI, RVG-ui, Kodak 5000, Kodak 6000, and Schick CDR demonstrated the excellent contrast resolution of the 18 sensors tested. The widest latitude was noted for PSP sensors, as expected, as well as Kodak 6000 and Kodak 5000. This study supports our conclusion that most systems perform comparably with intraoral film, and also allow for postprocessing of images, which is not possible for film-based images. Other factors that assume significance in this context are the availability of technical and customer support, frequency of both hardware and software upgrades, dimensions of the sensor, number of sensors needed in a practice and thus cost issues, the active area of the sensor, and conformance to the DICOM standard for seamless integration with other systems. CCD/CMOS sensors appear to offer the best contrast and spatial resolution, in addition to facilitating instantaneous image capture, and thus are recommended for endodontic applications. Careful and appropriate image processing further helps tease out the signal of interest. In an enterprise-wide setting or in larger private practice settings where multiple specialty areas exist, PSP-based sensors may be more cost-effective for large volume imaging, such as a full-mouth series of radiographs in multiple patients. However, at least one or two CCD/CMOS-based systems should be available for faster image acquisition, such as for endodontic purposes and intraoperative procedures. It is recommended that the literature be constantly reviewed for updates on digital radiography and advanced imaging modalities for specific endodontic applications, as hardware and software upgrades continue to make rapid progress. Previous studies have shown that most digital images performed comparably with conventional intraoral film for a variety of diagnostic tasks. The majority of these studies were done with earlier generation sensors. The recent advances in sensor technology have resulted in greatly enhanced image quality. This trend is expected to continue. Also of interest in the future would be the use of task-based, appropriate image processing parameters that would result in significant enhancement of the diagnostic information contained therein. Automation of this process would result in faster and more consistent image processing based on the diagnostic task. Such procedures are routinely carried out in medical radiology.

Three-dimensional imaging will continue to be used extensively as sensor characteristics improve and more robust software is introduced. As bit-depth and spatial resolution of images increase, 3D imaging will find more applications in endodontics. TACT is currently a research tool but holds promise of delivering a reliable imaging modality. More studies are still in order using high-resolution sensors for basis image capture, for diagnostic tasks in endodontics. CBCT or VCT provides a significantly faster image acquisition and reconstruction scheme, but the resolution is still inferior to that achieved by TACT. CBCT will continue to be explored for more applications in endodontics. However, it is imperative that data thus acquired using large area sensors are read by a board-certified radiologist. Occult pathology and incidental findings in adjacent regions are easily missed or not recognized if specific training in interpretation of regional anatomy has not been received. Additional imaging may be necessary if such pathology is discovered, including magnetic resonance imaging, nuclear medicine studies, or even medical CT for evaluation of soft tissues with and without the use of contrast agents. The advent of 3D imaging has provided the endodontist with tools that were not available to the clinician before, and facilitated interactive image manipulation and enhancement to visualize the area of interest as a 3D volume. Lack of distortion, magnification, artifacts associated with conventional radiography, and the relative low radiation dose in comparison with medical-grade CT will result in more clinicians adopting such technology to enable accurate diagnoses and treatment planning, in addition to long-term follow-up and evaluation of healing.

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