

Sponsored by

DEXIS
Digital Diagnostic Imaging

www.dexis.com

THE JOURNAL OF THE AMERICAN DENTAL ASSOCIATION



Filmless imaging: The uses of digital radiography in dental practice

PAUL F. VAN DER STELT

J Am Dent Assoc 2005;136;1379-1387

The following resources related to this article are available online at jada.ada.org (this information is current as of November 8, 2009):

Updated information and services including high-resolution figures, can be found in the online version of this article at:

<http://jada.ada.org/cgi/content/full/136/10/1379>

This article appears in the following **subject collections**:

Imaging <http://jada.ada.org/cgi/collection/imaging>

Information about obtaining **reprints** of this article or about permission to reproduce this article in whole or in part can be found at:

<http://www.ada.org/prof/resources/pubs/jada/permissions.asp>

Filmless imaging

The uses of digital radiography in dental practice

PAUL F. VAN DER STELT, D.D.S., Ph.D.

In 1895, German physicist Wilhelm Conrad Roentgen discovered the X-ray. Within two weeks after Roentgen made his discovery public, the first dental radiograph was made by German dentist Otto Walkoff, who placed in his own mouth small glass photographic plates wrapped in rubber dam and exposed them for 25 minutes. The characteristics and, more specially, the sensitivity of film have been

Digital radiography is a reliable and versatile technology that expands the diagnostic and image-sharing possibilities of radiography in dentistry.

improved considerably in the intervening 110 years. Patients and dental team members alike benefit from the reduction in necessary radiation dose that has resulted from the increased sensitivity of dental film. The primary principles of radiation protection in diagnostic radiology are justification (the patient will experience more benefit than harm from the exposure) and the "as low as reasonably achievable" (ALARA) principle (which also takes into account social and economic factors).

The first digital X-ray sensors for use in dentistry were introduced in the mid-1980s by Francis Mouyen (RVG, Trophy Radiologie, Croissy Beaubourg, France [now Trophy, A Kodak Company, Rochester, N.Y.]). The first dental digital system was capable only of acquiring a radiographic image; the image could not be stored on disk but had to be printed. However simple it appeared to be, it marked the start of a new era. Shortly thereafter, another system was developed by Per Nelvig and colleagues (Sens-A-Ray, Regam Medical Systems, Sundsvall, Sweden), and within a decade many more manufacturers entered the market. Digital

Background. As use of digital radiography becomes more common, many dentists are wondering if and how they can replace conventional film-based imaging with a digital system. This article briefly describes the different technologies used for digital radiography in dentistry.

The article provides general practitioners with a broad overview of the benefits and limitations of digital radiography to help them understand the role the technology can play in their practices.

Overview. The two technologies now available are solid-state systems and phosphor plate systems. Each has its strong points, and the choice of which to use depends on the type of dental practice. Image processing improves the diagnostic quality of the radiographic information. Advanced image-processing techniques, such as subtraction radiography, are available for specialized clinics.

Conclusions and Clinical Implications. Digital radiography no longer is an experimental modality. It is a reliable and versatile technology that expands the diagnostic and image-sharing possibilities of radiography in dentistry. Optimization of brightness and contrast, task-specific image processing and sensor-independent archiving are important advantages that digital radiography has over conventional film-based imaging.

Key Words. Digital radiography; image processing; diagnosis.



systems have improved considerably since then and now are a well-accepted and useful technology in dental diagnosis.

Dose reduction often has been emphasized as one of the biggest advantages of digital radiography. It will be shown later in this article that this can be argued. There is another reason, however, why digital radiography adheres to the ALARA principle in an important way: informa-

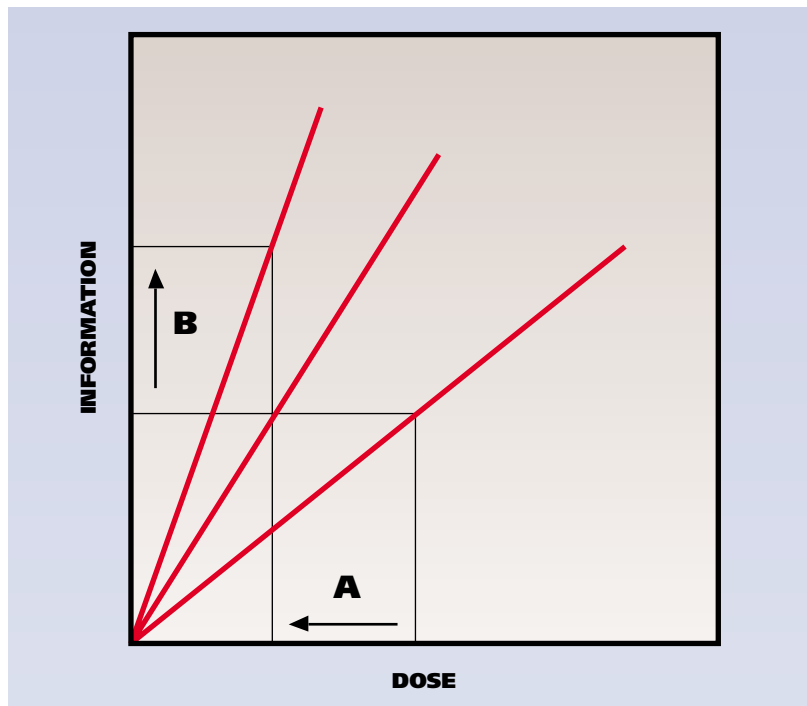


Figure 1. Relationship between radiation dose and information. The “as low as reasonably achievable” (ALARA) principle of radiation dosage aims at dose reduction while producing the same amount of information (A) or increasing the amount of information using the same dose (B). In both situations, the dose-information relationship is steeper.

tion recorded in the radiographic image can be made available to the observer more easily when the image is in a digital format than when it is in an analog format. The most significant advantages of digital imaging, therefore, are computer-aided image interpretation and image enhancement, in addition to the obvious options of standardized image archiving and image retrieval. Figure 1 shows that dose reduction and improvement of access to information both work in the same way and result in a more favorable dose-information ratio.

This article aims to provide general practitioners with an overview of the benefits and limitations of digital radiography to help them understand how it can be used in their practice.

THE TECHNOLOGY BEHIND DIGITAL RADIOGRAPHY

Digital radiographic images can be produced in different ways, some simple; flatbed scanners with a transparency adapter, slide scanners and digital cameras all can be used to convert an existing analog radiograph into a digital image. These approaches do not require a big investment, but nevertheless make it possible to bring

radiographic images into the digital loop. The images produced via this technique usually are referred to as “indirect digital radiographs.”

There are two more advanced technologies that create digital images without an analog precursor: “direct” digital images and “semidirect” digital images. Direct digital images are acquired using a solid-state sensor. The solid-state sensors are based on charge-coupled device (CCD)- or complementary metal oxide semiconductor (CMOS)-based chips. Semidirect images are obtained using a phosphor plate system.

Solid-state systems. *CCD technology.* Most solid-state sensors in digital dental radiography are based on CCD technology. CCD refers to the design of the electronic chip that is used to capture the radiographic image. The chip converts into an electronic signal the energy of X-ray photons hitting the sensor. To increase the efficiency of

this conversion, a scintillation layer is placed on top of the CCD. The scintillation layer converts X-ray photons into light photons, which then are absorbed by the CCD chip and converted into the electronic signal. This signal is sent to the computer by means of a cord between the sensor and the computer.

CMOS technology. Some solid-state sensors use CMOS technology. CMOS is not different from CCD technology in principle, but it does differ in terms of chip microarchitecture. In a CMOS chip, more of the electronic components controlling the conversion of photon energy into the electronic signal are incorporated into the chip itself. This simplifies the manufacturing process and, thus, reduces the costs of production. This architecture gave CMOS an advantage over CCD for some time. However, most digital cameras on the consumer market are based on CCD technology. The quality and production costs of CCD chips have benefited from this advantage of scale, and nowadays the image quality levels of CCD- and CMOS-based sensor systems are comparable.

Storage phosphor plate systems. Systems using photo-stimulable phosphor (PSP)—sometimes also referred to as “storage phosphor plate”

—systems use a plate covered with phosphor crystals. This phosphor layer is able to store the energy of the X-ray photons for some time. A scanner is required to “read” the image information from the plate, which it does by scanning the plate with a laser beam of near-red wavelengths. The energy is released from the phosphor layer, detected by an image intensifier and subsequently converted into digital image information. The latent image will remain in the phosphor plate before the scanning phase for minutes to hours, depending on the environment in which the plates are stored. They should not be exposed to bright light or warmth because this will release the energy before it is read by the scanner. After the plates are scanned, they are exposed to bright light that erases all remaining energy; the plates then can be used again.

CHOOSING A SYSTEM

Which system is the best choice for a dentist’s practice depends on how the practice is organized and how the system will be used.

CCD and CMOS systems. CCD and CMOS systems are connected to the computer by a cord. The connection can be via a wall box and the computer network. There are wireless systems on the market now, but these sensors are somewhat thicker than are systems with cords. The sensors are rigid and do not bend in the mouth of the patient and therefore could be more difficult for children to tolerate. The cord that connects the sensor to the computer may complicate the manipulations inside the patient’s mouth. The image produced by a solid-state sensor is available on the computer screen within a few seconds. As a result, such systems could be efficient aids in carrying out treatment such as an endodontic procedure, in which a second image easily can be made from a slightly different angle—for example, to make the second root canal better visible—with the sensor still in the same position. This could make a solid-state sensor the preferred sensor in a practice that focuses on endodontic procedures.

PSP systems. PSP systems are flexible to some extent, which will make it more comfortable for the patient. The plates require the extra step of the scanning procedure. The scanning time is somewhere between eight seconds for a single image and two minutes for a series of plates. Some systems take the same amount of time for the scanning of a series of up to eight plates, irrespective of the actual number of plates. The

advantage of PSP is that a single scanner can be shared among several operatories, similar to arrangements for a conventional film processor.

Extraoral systems. Extraoral systems, including for panoramic and cephalographic radiograph machines, exist as well in digital versions. Both CCD-based and PSP-based systems are on the market. The advantage of CCD-based systems is the direct availability of the image. Some PSP-based systems feature the ability to scan both intraoral and extraoral plates; for others, a special scanner is required to do this. For computed tomography (CT), a PSP-system still is the only option because of the way in which the tomographic image is produced.

DOSE REDUCTION

The reduction of the radiation dose the patient receives often is considered to be one of the most important advantages of digital radiography. However, it is questionable whether digital radiography really provides this benefit with regard to intraoral as well as extraoral imaging. Conventional extraoral radiography is based on screen-film cassettes. The intensifying screens already offer a significant dose reduction compared with that of nonscreen film-based imaging. Acquiring the image digitally, therefore, does not add much to the dose reduction in extraoral imaging.

Neither is the dose reduction realized by digital radiography clear with respect to intraoral imaging.¹ Phosphor plate systems have broad exposure latitude. This can be an advantage, because exposure conditions are not critical with respect to image quality. This implies that an overexposed image looks good even if the patient has received a higher dose than is necessary for a diagnostically useful image. Figure 2 shows that phosphor plate systems can provide good images even when the exposure time has been much greater than that required for film-based imaging. That means, however, that the user is not warned by an unsatisfactory image quality when the exposure time is too lengthy. CCD sensors, on the other hand, have a small exposure range. Overexposed images show completely saturated black areas, which give a clear indication to the user that the exposure time should be reduced. CMOS systems do not provide this clear indication but instead produce a darker image, comparable with what happens with film-based images, thus giving a signal that the exposure could be reduced.

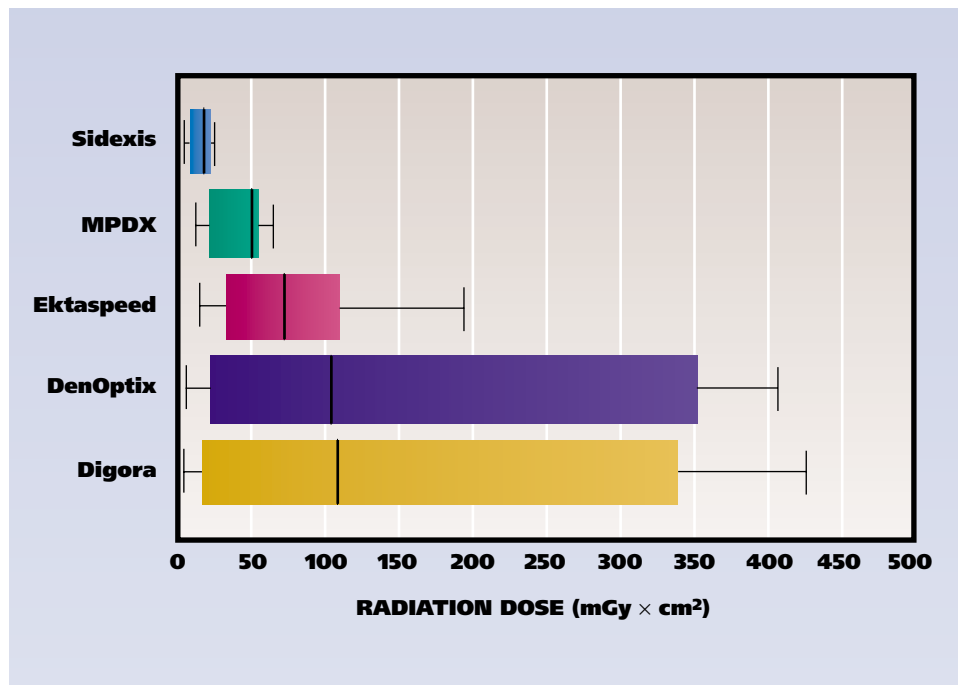


Figure 2. Radiation dose ranges for film, solid-state sensors and phosphor plate sensors. Minimum (left side of the box), maximum (right side of the box) and optimal (bold line in the box) dose levels are shown. Sidexis (Sirona, Bensheim, Germany) and MPDX (DMD Systems, Westlake Village, Calif.) are solid-state sensors. Ektaspeed Plus (Eastman Kodak, Rochester, N.Y.) is film. DenOptix (Gendex Dental Systems, Lake Zurich, Ill.) and Digora (Soredex, Tuusula, Finland) are storage phosphor plate sensors. The solid-state sensor systems have a narrow exposure range, which provides adequate feedback in case of under- or overexposure. The phosphor plate sensors produce good image quality over a much larger exposure range, reducing the risk of incorrect exposure settings, but at the same time introducing the risk of overexposure without being warned by inadequate image quality. mGy: Milligray. cm²: Square centimeters.

It should be clear that dose reduction for digital radiography is quite limited; it is possible only when the practitioner takes care to select the lowest exposure that still provides diagnostically useful images.

WHAT IS A DIGITAL IMAGE?

An important—maybe the most important—advantage of digital radiography is its ability to process the image data so that the information content of the image is more accessible for the human visual system.² The goal of radiography is not merely to capture an accurate image, but also to produce diagnostic information. Digital image processing can provide this information more effectively than can film-based imaging.

For a better understanding of the mechanism of image processing, it is good to know what a digital image actually is. Solid-state sensors and phosphor plate sensors in principle are not different with respect to the end result of the image acquisition process. The sensor system measures

the photon intensity of the X-ray beam after it has passed through the object (the patient). These measurements are done in a two-dimensional array of small regions of 20 to 30 square micrometers, called “pixels” (the abbreviation of “picture elements”) (Figure 3). The photon intensity is measured electronically on a scale of 256 gray values (0-255). Zero on this scale means that the maximum radiation is measured, which corresponds to black in the radiographic image, and 255 represents no radiation at all, or complete radiopacity (white). The measurements of the photon intensities for each pixel are sent to the computer and stored as an array of numbers representing the x and y coordinates and the photon intensity of each pixel. In fact, the digital image can be conceived as a table with columns and rows. The columns represent the x coordinates of the pixels and the rows the y coordinates. The values in each cell indicate the gray level of the pixel represented by that cell (Figure 3).

The numerical information contained in this array subsequently is used to display the gray values on the monitor screen. Some systems use a more detailed gray value scale, one that can contain up to 64,000 values, to express the photon intensity for each pixel; however, the image always is displayed on the monitor screen that uses only up to 256 gray values.

The table also can be used to perform image processing: a mathematical procedure is applied to the numerical representation of the digital image which results in a new set of pixel values. The resulting set of numbers then is used to display the processed image on the monitor screen (Figure 4). The algorithm between input and output image can be simple or complicated. A simple algorithm,

for instance, is the reversal of the order of the gray values, resulting in a negative of the original image. The example of Figure 4 shows the enhancement of contours, which are then recognized more easily by the human visual system than are small contrasts. More advanced algorithms can be thought of as well—resulting, for instance, in a three-dimensional reconstruction of radiographic information or the automated recognition of image features.

EXAMPLES OF IMAGE PROCESSING

Contrast and density. Correct exposure settings will result in an image with good contrast and density. An analog image will be too dark when the image has been overexposed, and no corrections can be made after the film has been processed.³ Obviously, this is different for digital images. Exposure conditions can be corrected to some extent: an overexposed image can be made lighter and, similarly, the density of an underexposed image can be made darker (Figure 5). This is not an excuse for not adhering to correct exposure settings, but it can help prevent at least some retakes when the exposure settings turn out to be incorrect after the image has been taken.

Correction of contrast and density can be done manually, but some software programs have the possibility to do a standardized contrast and brightness optimization, which will result in an objective and reproducible image quality.

On-screen measurements of digital images. Measurements of length, angle and area can be made on a digital image. The easiest way

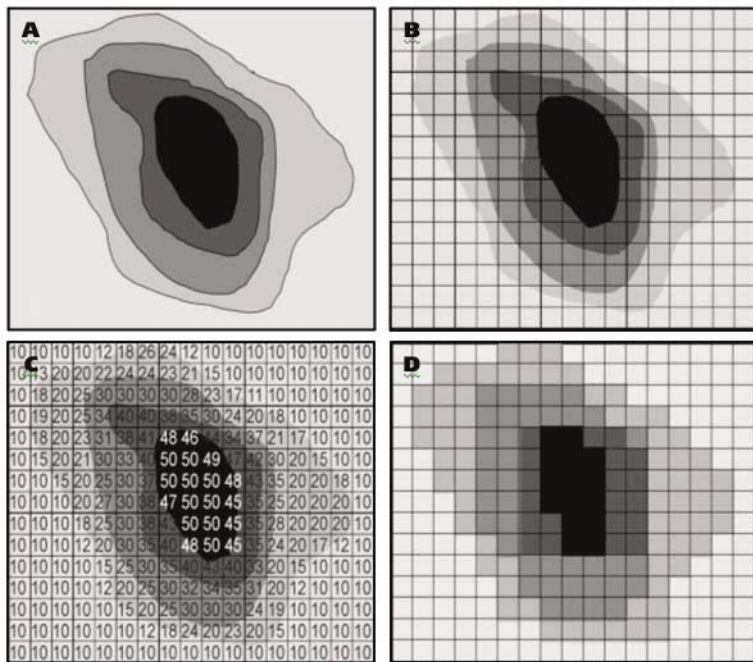


Figure 3. Schematic representation of a digital image. A. X-ray shadow. B. Image as detected by the digital sensor; each square is a pixel. C. Numerical representation of pixel values sent to the computer. D. Digital image on the computer screen.

is to express the measurement as the number of pixels; however, a more convenient method is to use millimeters or inches as the unit of measurement. Calibration of the magnification factor of a particular sensor is needed to convert pixel measurements in real length measurements. This usually is done by measuring the known length of an endodontic file that is included in the image and calculating the magnification factor from the ratio of the known file length and the measured length.

Some software programs are able to recognize the sensor system that was used to acquire the image and, subsequently, the pixel size and inherent image magnification. This information then is used to convert pixel measurements

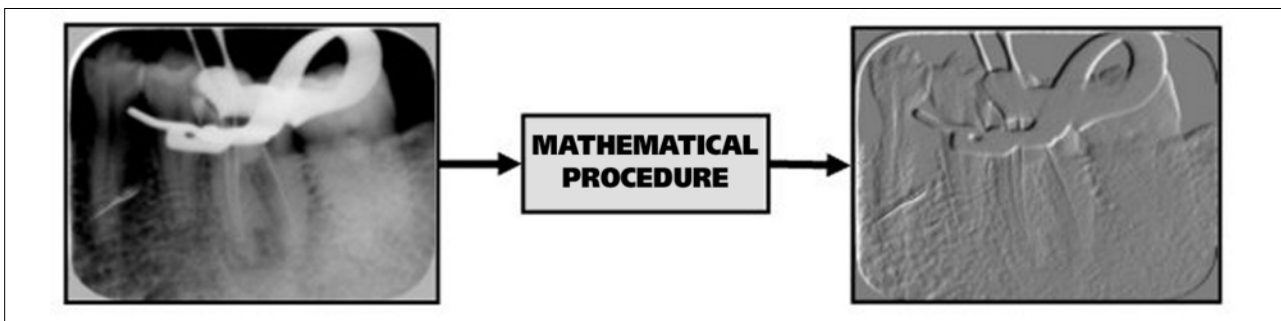


Figure 4. Principle of image processing. Contours have been accentuated in this image, which helps the visual system to detect small details, such as the tips of the endodontic files.

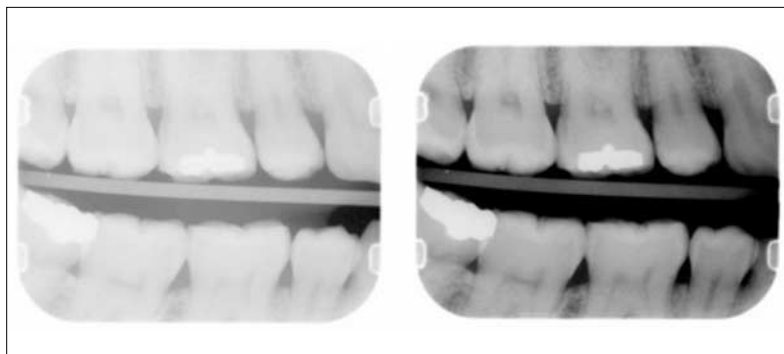


Figure 5. Underexposed image (left) and the same image after contrast optimization. It should be emphasized that brightness and contrast optimization never can be an excuse for improper exposure settings.

directly into real distances, without the use of a calibration tool. One should be aware of the fact that the latter method does not compensate for magnification caused by projective distortion; the calibration method using, for instance, an endodontic file does this to some extent.

Subtraction radiography. More advanced image processing is available to dental practitioners as well. Subtraction radiography originally was described by Ziedses des Plantes⁴ in the 1930s. Webber and colleagues⁵ and Gröndahl and colleagues⁶ introduced digital subtraction into dental radiography. Subtraction radiography is able to show small differences between radiographs taken a specified time apart. Subtraction of the pixel values of two images with the same projection geometry shows the differences and suppresses the structures of both images that are similar, which also is called “anatomical noise.”

The two images used for subtraction radiography must have identical projection geometry. Otherwise, the subtraction image shows the difference of the projection geometry instead of the difference between the first and the second exposure. Several reports have been published showing how to obtain identical images, based mainly on the use of film holders connected to individual bite-blocks. Recently, however, software solutions have been presented to reconstruct the second image according to the projection geometry of the first image, thus making the use of rigid film holders unnecessary; the software also can handle images obtained from different sensor systems, a situation that results in the images’ having different dimensional and magnification factors⁷ (Figure 6). These solutions facilitate subtraction radiography in gen-

eral practice, even without dedicated film holders.

SECURITY ASPECTS OF DIGITAL RADIOGRAPHY

The possibility of changing the look of a digital radiograph has raised the question of how trustworthy a digital image is. It is interesting to see that this question is asked in connection with digital images and less so with respect to film-based images.⁸ Clinical imaging software by default always should keep the original of the image,

even when contrast, density and other characteristics of the image have been adjusted by the user. In that way, it is always possible to go back to the original image. An electronic file has several time stamps that indicate the creation date and time of the file, the last time it was accessed, and if and when the file may have been changed. Of course, it is possible to fool the computer’s time setting, but this is not an easy task to accomplish when the image is part of a database structure and a log file is maintained of all database activities. It certainly is more complicated than changing the date of a film-based radiograph in the film mount. Often the software does not allow deletion of a digital image from the database, something that is quite simple to do in an analog archiving system.

Some companies have introduced the concept of using watermarks within their images when altered. This most likely would be a deterrent for those altering the images for fraudulent purposes. This security measure will not replace the principle that it is always the image in its original form that is stored in the database, but it will be an effective fraud protection when images are exported from the database and transferred to third parties.

It is interesting to see that most articles about fraudulent use of digital images are about how to change the image, not about how to detect an image that has been tampered with. The key issue is that insurance companies and dentists who receive images of referred patients should be aware of the possibilities of modifications in digital radiographs. In case of doubt, modifications can be recognized using standard image-processing procedures such as the measurement of the local noise level and irregularities of global contrast gradients. This, however, requires an

understanding of the standard characteristics of a digital image. When the reliability of an image is at issue, the practitioner should consult an expert in digital radiography. One also should appreciate that it usually is not a single radiograph that is the basis of the suspicion; in most situations, there is more evidence in the patient history and the treatment records that makes the case questionable.

In conclusion, there is no reason to consider digital radiographs less reliable than their analog counterparts when the source of the image can be shown, and when the image can be traced back to the original database.⁹

IMPLEMENTATION OF DIGITAL RADIOGRAPHY IN DENTAL PRACTICE

Organizational aspects. Some articles suggest that the conversion from analog to digital is as simple as just the replacement of the film processor and the viewing box. This, however, is a misconception, and it is likely that many practitioners do not appreciate the impact of this new technology on their practice management systems.¹⁰ Apart from the hardware and network infrastructure that is needed, and the selection of the most appropriate sensor system, the members of the dental team have to learn new skills: positioning the sensor in the mouth of the patient, using the software and performing computer maintenance. Digital radiography requires access to a computer, which in fact serves as the viewing box. The computer screen has to be placed in an ergonomically appropriate location that makes it easy to view the radiographic information during the treatment.

More importantly, the use of computers forces common procedures to be performed in a much more standardized way. Image acquisition takes place according to a strict protocol of consecutive steps, beginning with the selection of the name of the patient from whom the radiographs are going to be acquired from the imaging software's database or from the patient management system. That means that no radiographic image can be taken unless a patient is selected and that a radiograph that is taken always is connected with a patient. This

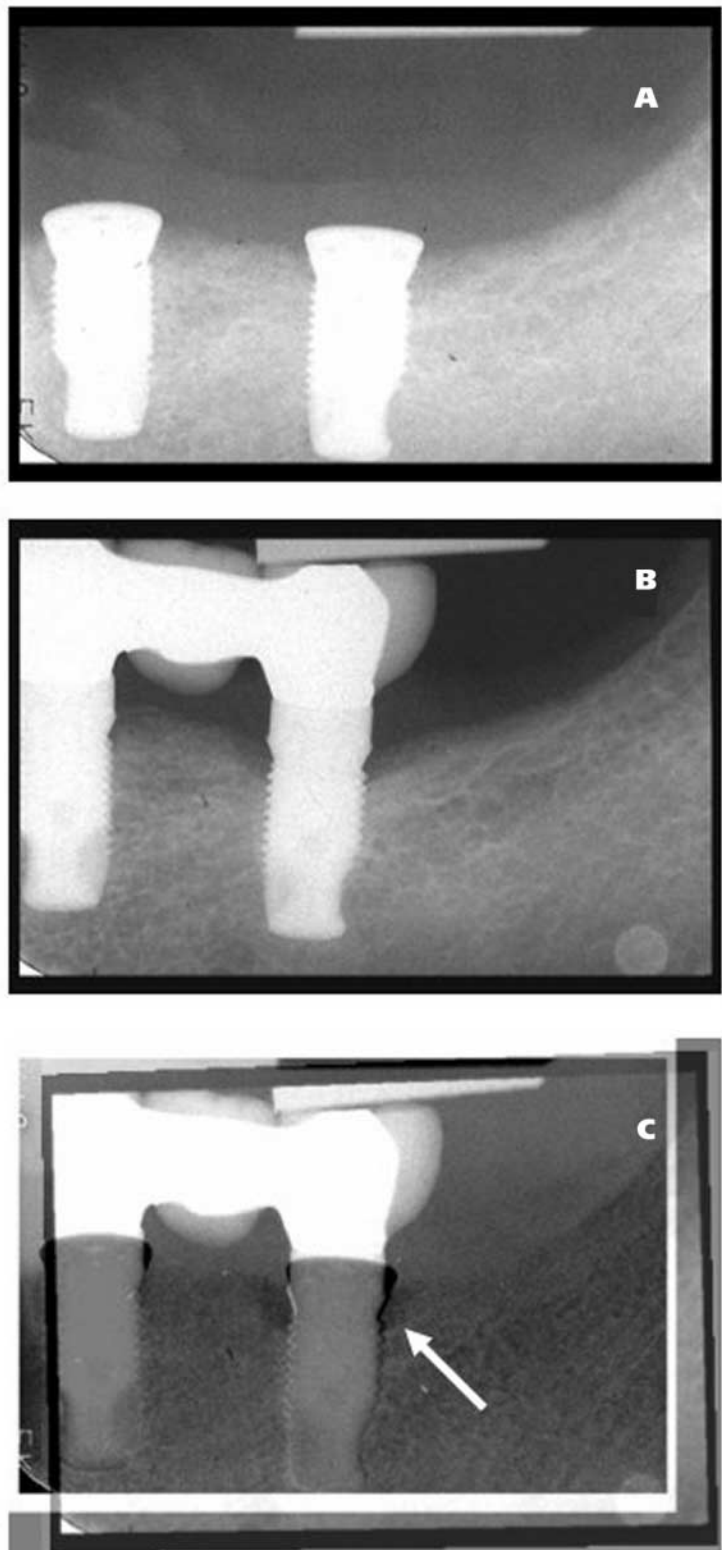


Figure 6. Subtraction radiography improved by geometric reconstruction (using Emago/Advanced Version 4.0, Oral Diagnostic Systems, Amsterdam) to match the two images. A and B. Original images. C. Subtraction result showing angular bone resorption (arrow). Photo reproduced with permission of Oral Diagnostic Systems, Amsterdam.

makes the work flow seemingly less flexible. However, the advantage is a more secure and reliable work flow, especially for the process of archiving and retrieving radiographic images.

An important aspect is the use of sensor systems from different manufacturers. Usually, the sensor is installed with the corresponding software and images are stored in the database provided by this software. This sounds logical, but in the long term it is not. Sooner or later sensors have to be replaced, or a sensor system from another manufacturer is added. It makes sense, therefore, to archive all images in a single database that is independent of a particular manufacturer. An essential requirement is that this kind of software is able to support sensor systems made by a large number of manufacturers. Especially in larger clinics and dental schools, sensor systems of different manufacturers will be used. When other people in the clinic or in the school need access to the image data, a single central database will provide this facility in a reliable and efficient way.

Diagnostic image quality. The quality of an image cannot be judged on the basis of a subjective assessment of what the image looks like. A “pretty” image is not always a good image when it relates to diagnostic imaging. The diagnostic image quality is the crucial parameter determining if an image is “good” or “not good.” Defining image quality is a complicated process because the image as such is part of a longer chain of procedures and actions, beginning with the sensor system used to acquire the image and finally resulting in the clinician’s diagnostic decision. Therefore, in studies of the quality of images produced by a particular sensor system, researchers usually measure the quality by displaying the images to a group of observers who have to perform a specific diagnostic task. They then compare the observations statistically with those of observations of one or more other sensor systems and of conventional film-based imaging.

Many studies have been published about a variety of diagnostic tasks performed on digital radiographic images: the assessment of caries in different degrees, the estimation of periodontal bone loss, the recognition of the length of an endodontic file with respect to the root length or the presence of periapical radiolucencies.

The majority of the studies conclude that the diagnostic quality of digital images certainly is adequate; digital images perform at least as well

as conventional radiographs and sometimes even better.¹¹⁻¹⁴ This is valid for both intraoral and extraoral radiography.¹⁵ CMOS sensors produce images of the same quality as those acquired with CCD sensors.¹⁶ There often is no significant difference in image quality of the various sensor systems on the market today.^{17,18} The effect of image enhancement is still questionable, though sometimes observers feel more comfortable when interpreting digitally enhanced images as compared with unenhanced images.¹⁹

When digital images are printed on photographic paper, the diagnostic quality can be comparable with that of images on traditional film.²⁰ It usually is recommended, however, that the clinician view images on a monitor screen, instead of printed on paper.

CONCLUSION AND FUTURE DIRECTIONS

The resolution of current sensors is more than adequate; higher resolution has no diagnostic advantage but will result in longer transmission times and more storage space requirements. Newer sensor systems capture the images at bit depths of 12 to 16, instead of the lower 8-bit depth that was common in the past. The higher bit depth will improve image quality under different exposure conditions.

Three-dimensional reconstruction and rendering of radiographic image data has been introduced recently in the form of cone beam CT and local CT. Both cone beam and local CT have imaging geometry comparable with that of conventional CT, but offer a higher resolution with a much lower radiation dose to the patient.

Digital radiography no longer is an experimental modality. It is a reliable and versatile technique that will improve the diagnostic possibilities of radiography in dentistry. ■

Dr. van der Stelt is a professor of oral and maxillofacial radiology, Department of Oral and Maxillofacial Radiology, Academic Center for Dentistry Amsterdam (ACTA), Louwesweg 1, 1066 EA Amsterdam, Netherlands, e-mail “p.vdstelt@acta.nl”. Address reprint requests to Dr. van der Stelt.

1. 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):1-5.

2. Lehmann TM, Troeltsch E, Spitzer K. Image processing and enhancement provided by commercial dental software programs. *Dentomaxillofac Radiol* 2002;31:264-72.

3. Pfeiffer P, Schmage P, Nergiz I, Platzer U. Effects of different exposure values on diagnostic accuracy of digital images. *Quintessence Int* 2000;31:257-60.

4. Ziedses des Plantes BG. *Planigrafie en subtractie*. Utrecht, Netherlands: The University of Utrecht; 1934.

5. Webber RL, Ruttimann UE, Gröndahl HG. X-ray image subtraction as a basis for assessment of periodontal changes. *J Periodontol Res* 1982;17:509-11.

6. Gröndahl HG, Gröndahl K, Webber RL. A digital subtraction technique for dental radiography. *Oral Surg Oral Med Oral Pathol* 1983; 55(1):96-102.
7. Van der Stelt PF, Geraets WG. Matching pairs of radiographs from different sensor systems for subtraction radiography (abstract 3052). *J Dent Res* 2003;(special issue B):82.
8. Tsang A, Sweet D, Wood RE. Potential for fraudulent use of digital radiography. *JADA* 1999;130:1325-9.
9. Berg EC. Legal ramifications of digital imaging in law enforcement. *Forensic Sci Commun* 2000;2(4). Available at: "www.fbi.gov/hq/lab/fsc/backissu/oct2000/berg.htm". Accessed Aug. 30, 2005.
10. Hellen-Halme K, Rohlin M, Petersson A. Dental digital radiography: a survey of quality aspects. *Swed Dent J* 2005;29(2):81-7.
11. Montes A, Gencoglu N. Canal length evaluation of curved canals by direct digital or conventional radiography. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 2002;93(1):88-91.
12. Kitagawa H, Farman AG, Scheetz JP, et al. Comparison of three intra-oral storage phosphor systems using subjective image quality. *Dentomaxillofac Radiol* 2000;29:272-6.
13. Vandre RH, Pajak JC, Abdel-Nabi H, Farman TT, Farman AG. Comparison of observer performance in determining the position of endodontic files with physical measures in the evaluation of dental X-ray imaging systems. *Dentomaxillofac Radiol* 2000;29(4):216-22.
14. Syriopoulos K, Sanderink GC, Velders XL, van der Stelt PF. Radiographic detection of approximal caries: a comparison of dental films and digital imaging systems. *Dentomaxillofac Radiol* 2000;29:312-8.
15. Molander B, Gröndahl HG, Ekestubbe A. Quality of film-based and digital panoramic radiography. *Dentomaxillofac Radiol* 2004; 33(1):32-6.
16. 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;32:408-11.
17. Schulze D, Rother UJ, Fuhrmann AW, Tietke M. A comparison of two intraoral CCD sensor systems in terms of image quality and inter-observer agreement. *Int J Comput Dent* 2003;6(2):141-50.
18. Benediktsdottir IS, Hintze H, Petersen JK, Wenzel A. Image quality of two solid-state and three photostimulable phosphor plate digital panoramic systems, and treatment planning of mandibular third molar removal. *Dentomaxillofac Radiol* 2003;32(1):39-44.
19. Woolhiser GA, Brand JW, Hoen MM, Geist JR, Pikula AA, Pink FE. Accuracy of film-based, digital, and enhanced digital images for endodontic length determination. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 2005;99:499-504.
20. Otis LL, Sherman RG. Assessing the accuracy of caries diagnosis via radiograph: film versus print. *JADA* 2005;136:323-30.