COVER STORY

DIGITAL RADIOLOGY
FACTS AND FICTIONS

STANLEY M. DUNN. PH.D.; MEL L. KANTOR, D.D.S.

ABSTRACT

Dental digital radiology is a rapidly changing field. The advantages and disadvantages are presented with an understanding that attention to fundamentals is paramount. The message for the near future is cautious optimism.

Digital imaging in dentistry is a rapidly changing field. Within the last five years new devices and computers systems have been introduced to record X-ray images and to manipulate those images using a variety of image processing operations. These developments have generated interest and excitement, as well as exaggerated claims of superiority.

Consider the following statements from two recent articles[1,2] in widely read trade journals (our emphasis added). "Specific areas of the radiograph can be enlarged for a *more detailed* analysis." "The contrast can be altered for *more precise viewing.*" "The high-resolution image, consisting of 256 gray levels, raises *your diagnostic capabilities* to a new level of excellence." "Detail also can be enhanced by *selecting the optimal* contrast level and gray scale." (The claim that digital radiography is the diagnostic equivalent of magnetic resonance imaging and computed tomography[2] is equally exaggerated. A discussion of this topic, however, is beyond the scope of this article.)

Do these new systems really increase diagnostic capacity? Are the results of the computer-based operations more exact than human observation? What are the advantages and disadvantages of computer-based digital imaging compared to traditional intraoral film-based radiography? Our purpose is to review fundamental concepts and explore some of the myths about digital imaging.

WHAT IS A DIGITAL IMAGE?

Digital images are not new; they have been a part of our lives for many years. A "digital image" is an image formed and represented by a spatially distributed set of discrete sensors and picture elements (pixels), respectively. Viewed from a distance, the image that you see appears continuous, but closer inspection reveals the individual pixels. Needlepoint and newspaper pictures are examples of digital images. A standard dental radiograph is, technically speaking, a digital

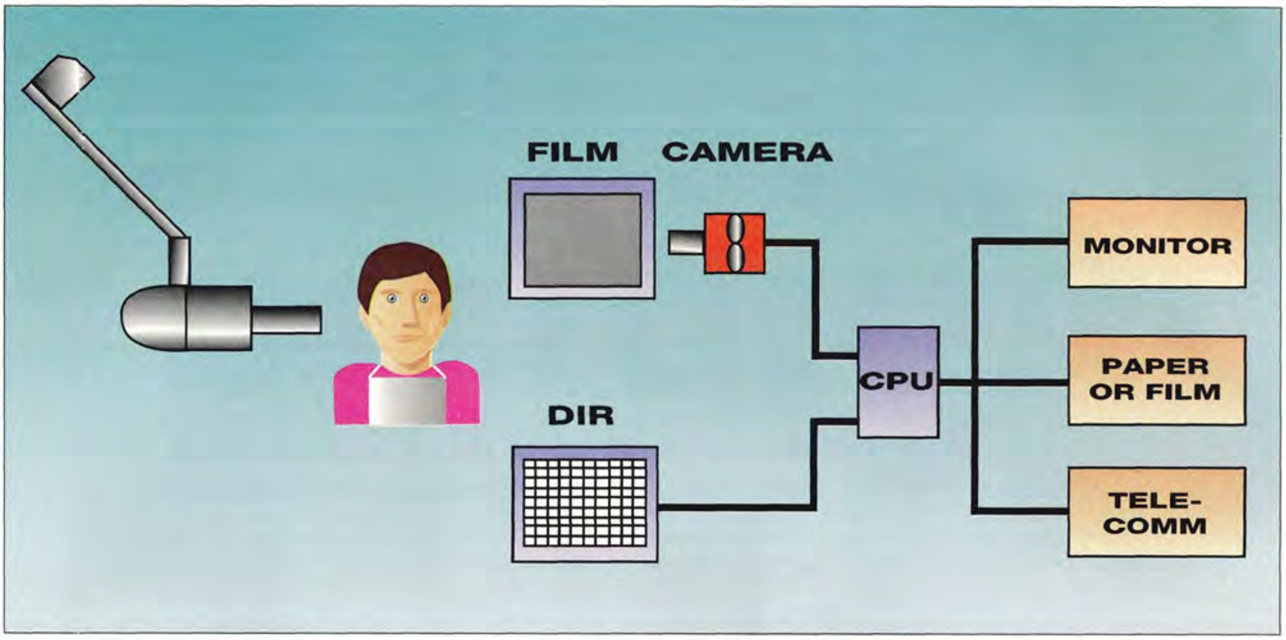

Figure 1. A digital imaging system may use a film intermediate that is "captured" with a video camera and sent to a computer (CPU) or a digital image receptor (DIR) that captures the X-ray image directly and sends it to the computer. Image processing is performed with the computer, and the resultant image displayed on a monitor, converted to hard copy (either paper or film) or transmitted to remote sites.

image formed by the distribution of individual silver grains in the photographic emulsion. The image of this page formed on your retina is a digital image captured by individual rods and cones (sensors) distributed over the surface of your retina. However, to represent a digital image in a computer additionally requires the quantization of the intensity of each pixel. In other words, a digital image is fully described by a numerical address of each pixel and a numerical value of the intensity of each pixel.

In the current vernacular "digital image" usually means an image that has been recorded with a non-film receptor. There are two types of non-film receptors for recording digital images. The first, a digital image receptor (DIR), collects X-rays directly. The second, essentially a video camera, forms digital images of radiographs (Figure 1).

A DIR is a device that directly forms a digital image without first recording the image on film. The heart of a DIR is a charge-coupled device (CCD) array, which is electronically connected to a computer. The CCD array in a DIR is either sensitive to X-rays or to visible light like the CCD array in a video camera. If the DIR uses a CCD array sensitive to visible light, then it must also use a scintillation screen to capture the X-rays with a coupling of the scintillator output to the CCD array. An intraoral DIR is placed in the mouth instead of film. The image area is limited by the size of the CCD array within the digital image receptor (Figure 2). The components of the four currently available digital radiography systems and their DIR sizes are given in Table 1.

Once the image is captured by the CCD, much like an image is captured by the silver halide crystals in film, it can be stored in the computer memory for image processing or displayed on a monitor for viewing. No film processing is needed and the image is available immediately.

Furthermore, fewer X-ray photons are needed to form an image on a CCD array than on dental X-ray film, thus reducing the patient exposure per image. The skin or surface exposure with a DIR is about 50 percent that of film for a single image (Table 2). However, the total patient dose depends on the number of images required to cover a region of interest, which in many applications is greater with DIRs than with film (a result of the smaller area of the CCD array).

What are the facts and fictions that pertain to computer-based digital images, especially when applied to dentistry?

DIGITAL IMAGE RECEPTORS FOR DENTAL RADIOLOGY

Fiction: DIRs produce images with the same information content as film.

Fact: The current technology limits the information content of DIRs, which is not on par with film. However, DIRs can capture and display images much quicker than film, and in the near future may be equivalent diagnostically with film-based imaging.

Technical comparisons of DIRs with film have shown that resolution, as measured by line-pair detection and modulation transfer function, for film exceeds that of DIRs.[4-6] For example, reported DIR resolution ranges between 7 and 10 line-pairs per millimeter (lp/mm): for film, it's between 12 and 14 lp/mm. Comparisons based on the ability to perceive artificial test patterns suggest that DIRs are not as good as[4] or are the equivalent of film.[6]

While these technical assessments suggest that film images contain more information than DIR images, the relationship to diagnostic efficacy is uncertain. Studies that compare observer preference for one image vs. another[7,8] do not measure diagnostic efficacy. To do this, we must compare the diagnostic test results for the different modalities to the truth that has been determined independently.

Most dental diagnostic tasks focus on dental caries, periodontal diseases and pulpal/periapical pathology.

There are few published studies comparing the diagnostic efficacy of DIRs to film. A study of occlusal caries detection showed that some digital images, acquired with a film intermediate or a DIR, were the diagnostic equivalent or better of conventional radiographs; other digital images acquired similarly but manipulated differently had poorer diagnostic efficacy than film.[9] A study of simulated periodontal bone lesions showed no difference among D-speed, E-speed and DIR images.[10]

TABLE 1

CURRENTLY AVAILABLE DIGITAL RADIOGRAPHY SYSTEMS AND IMAGE RECEPTOR SIZE.

RadioVisioGraphy (RVG)* Trophy (France) Scintillation screen/fiber optics/conventional CCD	19 x 28 mm
Flash-Dent Villa Systems (Italy) Scintillation screen/lenses/ conventional CCD	20 x 24 mm
Sens-A-Ray* Regam (Sweden) Direct exposure CCD	17 x 26 mm
Vixa* Gendex (Italy) Direct exposure CCD	18 x 24 mm
Dental film size #1 **Dental film size #2**	24 x 40 mm 31 x 41 mm

* FDA approved at this time (November 1993).

DIGITAL IMAGE PROCESSING

Fiction: Image processing increases the diagnostic information present in an image.

Fact: Image processing does not increase information content but can alter the relative weight of information germane to a specific diagnostic task so as to facilitate the retrieval of information.

Image processing refers to operations performed by computer on the digital image. Each system listed in Table 1 provides some image processing capabilities.

Before describing individual image processing operations, it

TABLE 2

RELATIVE PATIENT DOSE USING DIRECT IMAGE RECEPTORS COMPARED TO E-SPEED FILM.[3]

	%
E-speed film	100
RVG Model 32000	40
High resolution mode	160
Flash-Dent	40
High resolution mode	80
Sens-A-Ray	40
Vixa	30

is important to explain why it is a fiction that image processing increases the information content of an image. Your ability to see detail when viewing an image is constrained by:

- the properties of the image itself;
- the environment, such as the background lighting or lightbox glare;
- your visual system.

Optimizing each element is necessary to retrieve the maximum amount of information from the images. Let's consider each of the above in reverse order. Beyond correcting any vision problems with eyeglasses or contact lenses, there is little that can be done to optimize your visual system. Optimizing the environment is relatively straightforward and achieved by reducing ambient lighting, masking the image on the lightbox or monitor, adjusting the lightbox luminescence or monitor brightness and working in a room free from distractions.

Once these factors are optimized and controlled, the maximum diagnostic yield is limited by the original image. Once formed, there is no way to increase the information content of the image. However, not all of the information may be germane to the diagnostic task. The human visual system has a limited ability to discern the useful information (signal) from the superfluous information (noise). Image processing can be used to overcome this limitation of the human visual system by selectively presenting the information that we think will be useful and suppressing the rest.

The typical commercial DIR system includes image processing capabilities for contrast enhancement or modification, edge detection and magnification. Some manufacturers offer additional options.

Contrast enhancement electronically increases the apparent contrast between two adjacent areas that may be too subtle for the human eye to detect. A comparison with film radiography may be helpful. High kilovoltage peak (kVp) exposures produce a long gray scale with many shades of gray (information), but it may be difficult to perceive a difference between two adjacent regions if the difference is small. Low kVp exposures produce a short gray scale with fewer shades of gray (less information), but may be easier to detect differences between two adjacent regions.

In essence, switching from high kVp to low kVp is a contrast enhancement operation. While contrast enhancement sounds like a good thing, its value is actually task specific. Contrast enhancement can be performed in different ways. The technique that may be helpful in the radiographic detection of dental caries may be detrimental to the radiographic assessment of changes of the marginal periodontal bone.[11-13] In one study, one image processing operation appeared to improve caries detection, while a second available operation reduced diagnostic accuracy.[9]

Edge detection is the process of locating object boundaries in an image. Edges are usually defined as places of abrupt change in optical density, and, with a computer, are detected by identifying the pixels with a rapid change in image intensity. For example, in an anterior periapical film, you identify the incisal edge of the teeth by locating those points of rapid optical density change from the enamel (bright) to the oral cavity (dark). Computer-based edge detection is limited in its ability to separate real edges from "edges" caused by noise in the image.

Magnification (zooming) will increase the apparent size of the image. The information content of the image is limited by the resolution of the original CCD array. If the DIR resolution is 400 dots per inch (dpi), you'll never be able to see more than 400 dpi no matter how magnified the image. Additionally, there may be a "can't see the forest for the trees" effect with increasing magnification. Exceeding an optimal magnification may actually decrease the amount of information that you retrieve from a diagnostic image.[14]

Fiction: All image processing operations are equally useful.

Fact: Image processing operations are diagnostic task specific.

Earlier we said that image processing operations are used to "re-present" the information in an image. Image processing operations hide some of the detail (noise) that confound the features we think are of immediate interest. However, we do not know which operations (for example, contrast enhancement vs. edge detection) are applicable for each diagnostic task (for example, detecting caries vs. assessing the marginal bone or characterizing a central osseous lesion vs. assessing a fracture). The problem is akin to deciding what radiographs to make when the clinical signs and symptoms are equivocal. You might choose correctly, but then you might not.

In addition to considering which image processing operation to apply, we must consider how it is done. There are many different ways to perform each of the operations. They differ in the assumptions made about what information to keep and what to discard, and in the mathematical algorithms used to execute the operation. Although the details are unimportant to the clinical

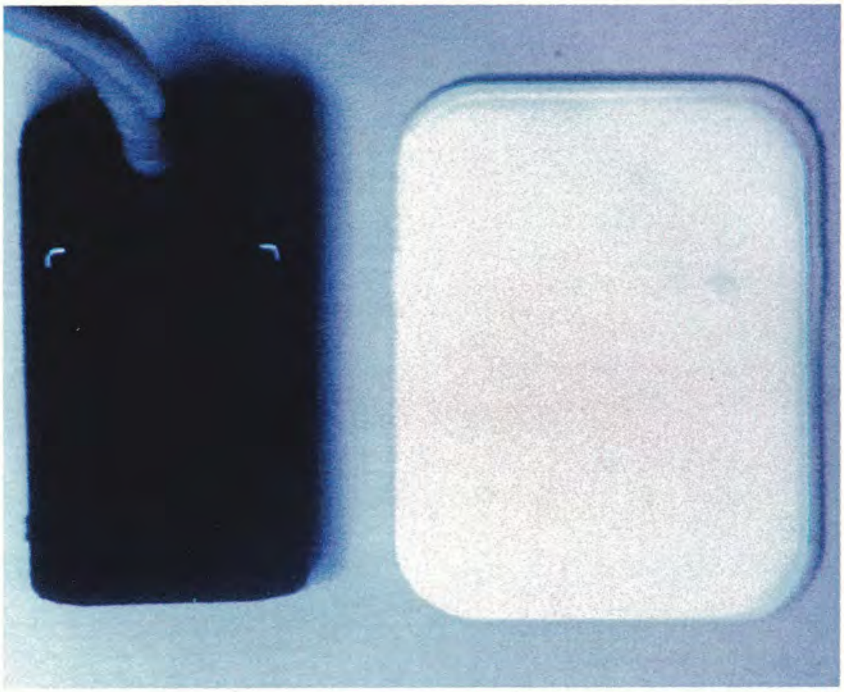

Figure 2. A typical digital image receptor shown with a standard No. 2 size intraoral dental film.

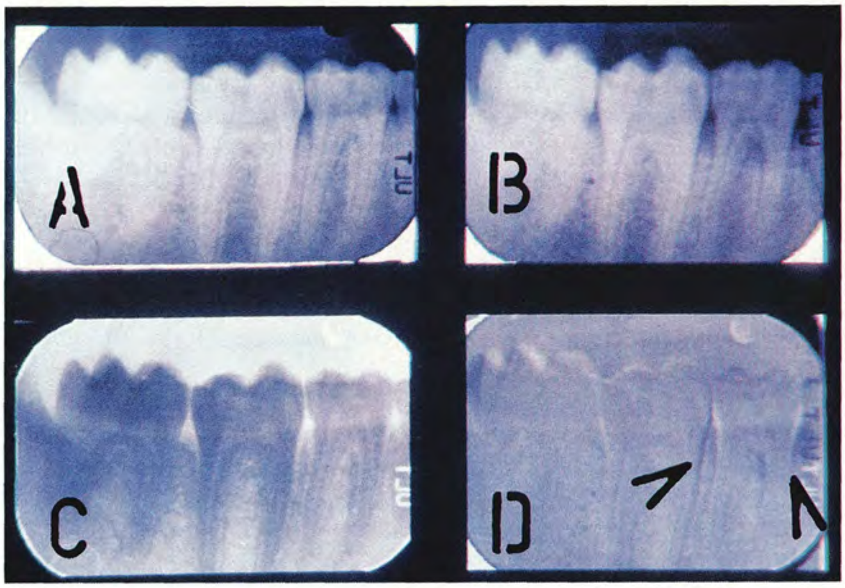

Figure 3. Subtraction radiography: (a) initial radiograph, (b) follow-up radiograph with suspected change, a periodontal defect in this case, (c) reversal of initial radiography, usually called a mask, and (d) the subtraction radiograph, which is the result of combining "b" and "c."

user, it is important to know that one manufacturer's contrast enhancement operation may produce a result very different from each of the other manufacturers' contrast enhancement operation.

SUBTRACTION AND REGISTRATION

Fiction: Digital radiography is necessary for image subtraction.

Fact: Photographic subtraction predates digital radiography by many years and is suitable for many subtraction tasks.

Photographic subtraction was introduced in 1935 as a method of eliminating (subtracting) unwanted or unnecessary information (noise) from a radiograph.[15] One of the common applications in medicine is cerebral angiography. A scout film of the head showing the bones is subtracted from the angiogram showing the bones and contrast media-filled blood vessels. The resultant subtraction film shows the fine detail of the cerebral vasculature without the distraction of the superimposed bone.[16] Subtraction is helpful in identifying small changes. Photographic subtraction has been used in the investigation of periodontal bone loss[17] and orthodontic cephalometric technique.[18] Photographic subtraction is labor intensive, but still used when very high-resolution information is needed, such as in peripheral angiography.

Digital subtraction combines the principles of digital radiography and photographic subtraction. Its advantages are the elimination of the reversal film and the ability to quantify the changes highlighted by the subtraction process. Applications of digital subtraction radiology include assessing changes of the marginal alveolar bone[19-21] and detecting carious lesions.[22,23] A dental example using periapical radiographs is shown in Figure 3.

Digital radiography and digital subtraction will not substitute for adhering to the principles and practices of basic intraoral radiography.

Fiction: Perfect registration is necessary for digital subtraction.

Fact: With photographic subtraction, perfect or near perfect registration is necessary for diagnostic information. The advantage of digital subtraction is the ability to manipulate mis-registered images to correct for geometric distortion before subtraction.

This does not mean that basic radiographic technique can be sloppy. Image registration techniques for digital images cannot correct all errors, but allow some latitude in film placement in the mouth and some latitude for density variation caused by film processing.

In the early days of digital subtraction radiography, investigators used occlusal stents to assure reproducibility of film placement and tube alignment, which are stringent requirements of photographic subtraction radiography. However, occlusal stents are inconvenient to store long-term and are subject to distortion. Taking advantage of some image projection geometry, you can relax the requirement for reproducibility of film placement by using a very long X-ray source to object (tooth) distance. However, this requires cephalometric-like equipment, which is not usually available in a general practice office.[24]

Recent advances in image processing techniques may allow for subtraction of typical day-to-day intraoral radiographs.[25,26] Once validated, this convenience may shift subtraction radiography from a research tool to a clinical application. However, even this technique has limitations and is subject to the cardinal rule of all computer applications: garbage in-garbage out. Digital radiography and digital subtraction will not substitute for adhering to the principles and practices of basic intraoral radiography.

QUANTITATIVE DIGITAL IMAGING

Fiction: Digital imaging increases the accuracy of quantitative information in the digital image.

Fact: Digital imaging may make quantitative measurements easier. It does not increase accuracy, though it may increase precision.

The terms "accuracy" and "precision" may be either confusing or synonymous for some, so it is helpful to clarify the distinction. Accurate measurements are free from error. Precise measurements have exactness, but are not necessarily accurate. For example, measuring the tooth length on a significantly foreshortened radiographic image can be done with great precision, but clearly will not be an accurate or true measure of the tooth length.

It is very important to differentiate accuracy and precision. Digital imaging may increase measurement precision, but not accuracy. Good basic radiographic technique with attention to image geometry and processing (if using film) will assure accuracy. Digital image analysis of poor radiographs may yield precise (many significant digits) but erroneous (inaccurate) results. Similarly, incorrect X-ray exposure (kVp or mAs) or variability of DIRs sensitivity caused by fluctuations in electrical current will also yield inaccurate but precise results. Computers with their many numeric and precise results often suggest accuracy even when not warranted.

More hardware, memory or computing power does not automatically mean more precision. The improvement comes when all system components (image acqusition devices, computer, image display and software) are compatible and operate at the same level of precision. For example, upgrading the computer from 16 to 32 bits (binary digits needed to represent a number in a computer) will not improve precision unless all of the other components are similarly changed. Accuracy requires attention to details outside of a precise digital imaging system.

QUALITATIVE VISION AND OBSERVER PERFORMANCE

Fiction: What you see is what there is. (Is seeing believing?)

Fact: Image display, viewing conditions and individual observer performance all affect information retrieval from an image (what you see). What there is remains invariant.

Acquiring a radiographic image, whether film or digital based, is only half the story. The image must be displayed, viewed and interpreted. The interpretation of a radiographic image is a high-level cognitive activity based on observer knowledge and experience. Explaining this activity is best left to the cognitive psychologist. However, image display and image viewing are factors that are, perhaps, more easily understood and certainly more easily controlled.

The interpretation of a radiographic image is a high-level cognitive activity based on observer knowledge and experience.

The study of human performance of routine mental tasks is called psychophysics. Examples pertinent to dental radiology include assessing the influence of viewbox and ambient light on radiographic viewing,[27] measuring eye movement of observers searching a radiographic image for essential diagnostic information[28] and mapping the neural pathways in the visual cortex during image viewing.[29]

Image display options in film radiography are limited. An overexposed image might be viewed successfully using an exceptionally bright "hot-light." Of course, for viewing a properly exposed radiograph, you should mask the viewbox to eliminate glare and reduce ambient light. Viewing films using an overhead fluorescent light or window lighting puts the observer at a disadvantage and denies the patient the benefit of an optimal radiographic viewing.

Digital image displays offer greater flexibility, but there are limits. For a contrast difference to be detected, it must exceed a certain threshold compared to the background density. That is, a small contrast difference is detectable in a dark background but not in a light background. Thus, if you are looking at an image on a monitor and the room light is bright, it will be difficult—perhaps impossible—to see a small contrast difference. If the room is darkened and the monitor brightness is turned down, then it is easier to see the small contrast difference. Many incipient lesions may go undetected because the image display and viewing conditions are not appropriate.[27]

Another option with digital imaging is the ability to magnify an image electronically and display it on a monitor. Consider a video camera. The image formed on the CCD is very small. The scene of a family holiday party has been reduced through the lenses of the video camera and focused onto the CCD array. When you play the tape back on a wide-screen television, the image is magnified by the electronics of your television. If you are sitting too close, the magnified image may appear unsharp or out of focus.

A similar process occurs with DIRs and video monitors. The X-rays striking the DIR produce a reduced or life-size image of the teeth, which is then magnified under computer control and displayed on the monitor. There may be an optimal magnification for a particular diagnostic task. For example, magnification up to fourfold seems to enhance caries detection, but magnification beyond that results in a decrease in diagnostic accuracy.[14]

Changing brightness or contrast on the monitor may make the image appear more correct, but the range of optical densities is limited by the image recorded. If the room is dark when you make the holiday video, you can increase the brightness on the television to improve the picture somewhat, but subtle details will still be missing. The most expensive television set available can not improve a bad recording. The same is true for DIRs and display monitors.

SUMMARY

Fiction: Digital imaging in its current form is the successor to film for radiographic-based diagnostic tests.

Fact: Digital imaging has many potential benefits yet to be fully explored or demonstrated.

Our final message is one of cautious optimism. Our caution comes from experience. We recall the flurry of activity in the 1980s when dental xeroradiography was introduced.[30] The advantages seemed numerous: no chemistry, final images in 20 seconds and the ability to view them with either transmitted or reflected light. Nonetheless, xeroradiography never became a practical clinical application. While we do not believe that digital imaging will be the xeroradiography of the 1990s, we do believe that digital imaging is still in the development and evaluation phase.

Recall that a digital image can be obtained in two ways: using a film radiograph intermediate or directly with a digital image receptor. If a film intermediate is used, the digital image can be no better than the film itself. Attention to fundamentals is paramount. However, minor geometric or densitometric (due to improper exposure or processing) errors can be corrected if the range of error is known or can be estimated. Geometric errors are usually easier to recover from as there is more control of projection geometry. In any imaging system, the result can not be better than the weakest link. If DIRs are used, their physical properties such as size and X-ray sensitivity are limiting. Poor receptor placement or incorrect imaging geometry will produce a non-diagnostic image just as surely as if film were used.

The new world of digital imaging will also have its advantages. Images can be produced rapidly and displayed almost instantly, which may prove useful for intraoperative imaging during endodontic procedures and some surgeries. As with hand-held calculators, we anticipate a decreased cost and increased utility of DIRs in the next five to 10 years. This may some day result in DIRs replacing film for general use, eliminating the need for processors, chemistry and darkrooms.

Combining radiology with telecommunications has produced teleradiography, the transmission of radiographic images over telephone lines. In medicine, sharing images with a colleague to whom you have referred a patient, or consulting with a colleague at a distant facility is now feasible. Applications in dentistry may become commonplace in the future. On a historical note, the Western Union Company offered telegraph transmission of dental images as early as 1929.[31]

New technology is often impressive and attractive. Clinicians may be drawn to it and incorporate it into their practice before its effectiveness has been demonstrated. In discussing technological advances in health care in 1991, Dr. Samuel O. Thier, then president of the Institute of Medicine, said, "If we cannot determine what is useful and appropriate, then it is unlikely that we will make wise choices about what we wish to do."[32] Our intent has been to provide basic and background information that will serve as the basis for making wise choices about digital imaging in your practice. ■

Dr. Dunn is associate professor, Department of Biomedical Engineering, College of Engineering, Rutgers University; and adjunct associate professor, Division of Oral and Maxillofacial Radiology, UMDNJ-New Jersey Dental School, 110 Bergen St., Room C827, Newark, N.J. 07103-2400. Address reprint requests to Dr. Dunn.

Dr. Kantor is associate professor and director, Division of Oral and Maxillofacial Radiology, UMDNJ-New Jersey Dental

School; and clinical associate professor, Department of Radiology, UMDNJ-New Jersey Medical School.

The authors thank Dr. Paul F. van der Stelt of the Department of Oral Radiology, ACTA, Amsterdam, The Netherlands; Dr. Thomas Tompkins of Hillsborough, N.J.; and Dr. Harold E. Rogers of Clayton, N.C., for reviewing early drafts of this paper.

1. Lackey AD. Advancing computer technology into the dental treatment room. Dent Today 1993;12(8):30-5.

2. Mason F. High-tech developments in the dental office. Dent Products Report 1993; 27(8):10-11, 116.

3. van der Stelt PF, Sanderink GCH. Direct digital intraoral radiography in dentistry. In: Burdea GC, Taylor RH, eds. Computer integrated surgery. Cambridge: MIT Press; (In press:1993).

4. McDonnell D, Price C. An evaluation of the Sens-A-Ray digital dental imaging system. Dentomaxillofac Radiol 1993;22:121-6.

5. Nelvig P, Wing K, Welander U. Sens-A-Ray: A new system for direct digital intraoral radiography. Oral Surg Oral Med Oral Pathol 1992;74:818-23.

6. Benz C, Mouyen F. Evaluation of the new RadioVisioGraphy system image quality. Oral Surg Oral Med Oral Pathol 1991; 72:627-31.

7. Wenzel A, Hintze H. Perception of image quality in direct digital radiography after application of various image treatment filters for detectability of dental disease. Dentomaxillofac Radiol 1993;22:131-4.

8. Fujita M, Kodera Y, Ogawa M, Wada T, Doi K. Digital image processing of periapical radiographs. Oral Surg Oral Med Oral Pathol 1988;65:490-4.

9. Wenzel A, Hintze H, Mikkelsen L, Mouyen F. Radiographic detection of occlusal caries in noncavitated teeth. Oral Surg Oral Med Oral Pathol 1991;72:621-6.

10. Furkart AJ, Dove SB, McDavid WD, Nummikoski P, Matteson S. Direct digital radiography for the detection of periodontal bone lesions. Oral Surg Oral Med Oral Pathol 1992; 74:652-60.

11. Mol A. Computer aided diagnosis of periapical bone lesions. PhD Thesis. Vrije Universiteit te Amsterdam;1992.

12. Heaven TJ, Firestone AR, Feagin FF. Computer-based image analysis of natural approximal caries on radiographic films. J Dent Res 1992;71:846-9.

13. Wenzel A. Effect of image enhancement for detectability of bone lesions in digitized intraoral radiographs. Scand J Dent Res 1988;96:149-60.

14. Scaf G, Kantor ML, Walsh SJ. Effect of magnification on caries detection with RadioVisioGraphy (RVG). J Dent Res 1993; 72(Special Issue):255.

15. Curry TS, Dowdey JE, Murry RC. Christensen's introduction to the physics of diagnostic radiology. 3rd ed. Philadelphia: Lea & Febiger; 1984:290-4.

16. Welander U. Multicolor combination images in subtraction angiography. Acta Radiol 1969; Supplement. 290.

17. Lurie AG, Greenberg RJ, Kornman KS. Subtraction radiology demonstrates crestal bone loss in experimentally induced marginal periodontitis. Oral Surg Oral Med Oral Pathol 1983; 55:537-41.

18. Kantor ML, Phillips CL, Proffit WR. Subtraction radiography to assess reproducibility of patient positioning in cephalometrics. Am J Orthod Dentofac Orthop 1993;104:350-4.

19. Okano T, Ohki M, Mera T, Soejima H, Ishikawa I, Yamada N. Quantitative evaluation of proximal bone lesions using digital subtraction radiography. Dentomaxillofac Radiol 1988;17:99-103.

20. Nicopoulou-Karayianni K, Bragger U, Burgin W, Nielsen PM, Lang NP. Diagnosis of alveolar bone changes with digital subtraction images and conventional radiographs. Oral Surg Oral Med Oral Pathol 1991;72:251-6.

21. Okano T, Mera T, Ohki M, Ishikawa I, Yamada N. Digital subtraction of radiograph in evaluating alveolar bone changes after initial periodontal therapy. Oral Surg Oral Med Oral Pathol 1990;69:258-62.

22. Nummikoski PV, Martinez TS, Matteson SR, McDavid WD, Dove SB. Digital subtraction radiography in artificial recurrent caries detection. Dentomaxillofac Radiol 1992; 21:59-64.

23. Wenzel A, Halse A. Digital subtraction radiography after stannous fluoride treatment for occlusal caries diagnosis. Oral Surg Oral Med Oral Pathol 1992; 74:824-8.

24. Jeffcoat MK, Reddy MS, Webber RL, Williams RC, Ruttiman U. Extraoral control of geometry for digital subtraction radiography. J Periodont Res 1987; 22:395-402.

25. Dunn SM, van der Stelt PF. Recognizing invariant structure in dental radiographs. Dentomaxillofac Radiol 1992; 21:142-7.

26. Dunn SM, van der Stelt PF, Ponce A, Fenesy K, Shah S. A comparison of two techniques for digital subtraction radiography. Dentomaxillofac Radiol 1993; 22:77-80.

27. Arnold LV. The radiographic detection of initial carious lesions on the proximal surfaces of teeth. PhD Thesis. Rijkuniversiteit te Utrecht; 1983.

28. Schouten E, van der Stelt PF. Expertise in interpreting dental radiographs. Proceedings 14th International Conference of the IEEE Eng in Med and Biol Sci. Paris 1992:1105-6.

29. Marr D. Vision: a computational investigation into the human representation and processing of visual information. San Francisco: Freeman;1982:20-38.

30. White S, Hollender L,Gratt B. Clinical trials of intraoral radiography. JADA 1979;810-6.

31. Sending dental x-rays by telegraph. Dent Radiogr Photogr 1929:2(2):16.

32. Thier SO. Dental education in the future. J Dent Educ 1991;55:353-5.