Review Article

DIGITAL IMAGING MODALITIES FOR DENTAL PRACTICE

MAMORU WAKOH and KINYA KUROYANAGI

Department of Oral and Maxillofacial Radiology, Tokyo Dental College,
1-2-2 Masago, Mihama-ku, Chiba 261-8502, Japan

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Abstract

The introduction of the computed tomograph in the 1970s revolutionized medical diagnosis by initiating the transition from analogue to digital imaging. During this period, more specialized equipment for image processing was developed, such as cathode-ray tubes for image display, special sensors for image acquisition, and storage devices for image archiving. Digital imaging systems designed exclusively for use in dentistry were developed in the latter half of the 1980s. Some are now being clinically applied under conditions of close scrutiny to determine diagnostic accuracy, image quality, and radiation exposure to patients. This article reviews the enabling technologies of digital systems used in dentistry, and focuses upon intraoral digital imaging systems, concepts for digital image acquisition, and variations in radiation dose and their effects on diagnostic accuracy of caries detection.

Key words: Digital image—Imaging modalities—Intraoral radiography—Dentistry

TRANSFORMATION INTO DIGITAL IMAGES SUITABLE FOR DENTAL APPLICATIONS

Conventional radiographic films that pass through all the functions of the imaging chain, namely image acquisition, chemical processing, transportation, storage and image display, have been important for image-based diagnosis. However, equipment such as cathode-ray tubes for image display, special sensors for image acquisition, and storage devices for image archiving has become more specialized. Thus, the independent performance of these functions is a key feature of digital imaging systems. In addition, these systems have the advantages of a lower radiation dose, image processing, image reconstruction, and teleradiology.

The turning point from film-based to digital radiography dates back to 1972 when G.N. Hounsfield introduced his new invention called computerized transverse axial scanning. The first unit accommodated only the patient’s head, and the scan time for one slice was approximately 4.5 minutes with an additional 1.5 minutes for reconstruction. This technique evolved into the computed tomograph, which requires only seconds to complete a full body scan and uses a helical scan.
with a multi-detector. Digital imaging has been applied to dentistry since the 1980s to diagnose paranasal sinus and temporomandibular joint diseases, as well as oral and maxillofacial trauma. Advances in magnetic resonance imaging, ultrasonography, and positron-emission tomography also propelled radiology towards digital image interpretation and diagnosis.

The first intraoral direct digital imaging system, RadioVisioGraphy (RVG) (Trophy Radiologie, Vincennes, France), was introduced into dental diagnosis in 1989 as a replacement for film-based intraoral radiography. It included a charge-coupled device (CCD) sensor and processing unit with cathode-ray tubes for image display. The first photostimulable phosphor (PSP)-based intraoral system, DigoRA (Orion Co./Soredex, Helsinki, Finland), became commercially available in 1994. These technologies have undergone considerable improvement, and many other systems have emerged that include novel CCD, PSP, and complementary metal oxide semiconductor (CMOS) designs. Sensors with dimensions suitable for use in the mouth have been developed due to progress in miniaturization of electronic circuitry.

Extraoral digital imaging using analog silver halide film has also progressed. Extraoral systems for dental purposes were originally based mostly on PSP or CCD systems. In 1985, PSP-based panoramic radiography appeared with the advantages of reduced exposure and image enhancement. This technology with PSP applied to a CR (Computed Radiography) System (Fuji Medical System, Co., Tokyo, Japan) has been used for extraoral projections and image analysis including dental panoramic radiography. In 1993, McDavid et al. described a prototype digital panoramic system that uses a solid-state linear array of photodiodes. Arai et al. were the earliest Japanese pioneers to investigate digital panoramic dental radiography using a camera system. At least five commercially available systems for CCD-based panoramic radiography are currently on the market. The DigiPan Universal (Trophy Radiology, Marnel-la-Vallee, France) and the Orthophos DS (Sirona AG, Bensheim, Germany) were previously discussed in relationship to radiation dose reduction.

This article mainly reviews the enabling technologies of intraoral digital imaging systems, namely concepts for digital image acquisition, variations in radiation dose, and the effects of dose on the diagnostic accuracy of caries detection.

### CONCEPTS FOR DIGITAL IMAGE ACQUISITION

Dental digital images are acquired by several means. These include indirect imaging from conventional radiographs using a flatbed scanner, semidirect imaging using a PSP detector and direct imaging based on a solid-state electric detector, such as CCD or CMOS sensors. Table 1 shows some of the intraoral

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**Table 1** Specification of some intraoral digital imaging systems

<table>
<thead>
<tr>
<th>Systems</th>
<th>Sensors</th>
<th>Pixel number</th>
<th>Pixel size (μm²)</th>
<th>The number of gray levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sens-A-Ray</td>
<td>CCD</td>
<td>576×385</td>
<td>45×45</td>
<td>256</td>
</tr>
<tr>
<td>CDR</td>
<td>CCD</td>
<td>720×400</td>
<td>48×48</td>
<td>4,096</td>
</tr>
<tr>
<td>CompuRay</td>
<td>CCD</td>
<td>768×512</td>
<td>39×39</td>
<td>1,024</td>
</tr>
<tr>
<td>VIXA</td>
<td>CCD</td>
<td>384×288</td>
<td>63×63</td>
<td>256</td>
</tr>
<tr>
<td>DigoRA</td>
<td>IP</td>
<td>560×416</td>
<td>70×70</td>
<td>1,024</td>
</tr>
<tr>
<td>DenOptix</td>
<td>IP</td>
<td>969×733</td>
<td>42×42</td>
<td>65,536</td>
</tr>
<tr>
<td></td>
<td></td>
<td>485×367</td>
<td>85×85</td>
<td>256</td>
</tr>
</tbody>
</table>

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digital imaging systems that are currently available. Fig. 1 shows examples of systems with a CCD sensor or with an imaging plate (IP) and laser scanner.

1. **Indirect digital image acquisition**

Dental diseases were diagnosed before the advent of PSP and CCD sensors using digitized images of conventional, intraoral or panoramic films obtained from flatbed scans of transparencies. The resolution of digitized radiographs is generally from 150 to 900 dpi. When the resolution is too high, the individual silver grains of the X-ray film become visible, and the quality of such digital images is limited.

2. **Semidirect digital image acquisition**

Semidirect digital systems including intraoral, panoramic, cephalometric and other extraoral types of radiography for dental applications are PSP-based. In 1975, a general method of using scanning optics to release energy from a storage phosphor and of digitizing the information was patented, and the first technical paper describing this methodology was published in 1983. In this system, image acquisition, chemical processing, transportation and storage, as well as image display are performed independently of each other.

A storage phosphor material has to satisfy the following conditions. First, the compound must create and store the latent image without appreciable degradation until it is ready to be scanned by laser. Second, the phosphor must be sufficiently simulated by light that the stored energy in the latent image can be released. Third, the released energy must have a wavelength that can be readily detected in the presence of the stimulating...
light. The most popular type is europium-doped barium fluorohalide, which acts as an activator to create luminescence centers. The fluorohalide is mixed with a polymer that binds the storage phosphor crystals to a base. The phosphor is covered with a protective coating. When the phosphor is exposed to X-radiation, an electron of the europium ion is excited to the conduction band and trapped in the crystalline lattice of the storage phosphor, where it causes luminescence. When the excited fluorohalide complex is stimulated by red and green laser lights, fluorescent light proportional to the X-ray dose absorbed is generated and converted into an amplified electric signal. This analog signal is converted to digital form by an analog-to-digital (A/D) converter. In other words, analog signals are converted into a fixed number of values, depending on the number of bits that are used for the purpose. Intraoral systems usually store images as 8-bit data. In general, thin phosphor layers achieve better spatial resolution and sharpness than thick layers, but current intraoral systems have a resolution of about 6 to 8 lp/mm, except for the DenOptix system, which has a spatial resolution of 12 lp/mm\textsuperscript{16}. This value is almost equal to that of CCD-based systems.

3. Direct digital image acquisition

Direct digital imaging can be based on solid-state electric detectors such as CCD or CMOS sensors. Direct sensor systems include a CCD or CMOS sensor, a processing unit, a digital interface card, computer, and software. Some systems are supplied with a dedicated timer so that X-ray production and image acquisition can be synchronized. These systems are hard-wired to the X-ray equipment, and the sensor automatically starts image acquisition when it detects an increase in the radiation level. There are two major types of CCD used in intraoral radiography: those that use a scintillation screen to expose the CCD chip, and those that use an image sensor that is directly exposed to X-radiation (Fig. 2). The first group of these systems uses an optical coupler, either a fiber-optic or a series of lenses, to transfer light from a scintillation screen to a CCD that is not resistant to frequent direct exposure to X-radiation, resulting in image distortion and image density\textsuperscript{2,36,41,49}. The second group of these sys-
tems uses “hardened” CCDs which are more sensitive and resistant to X-radiation. This imaging process results in decreased optic distortion, but ground haze or noise presents a problem.

The CCD sensor was first developed at the Bell Laboratories of AT&T for video applications in the late 1970s. These sensors consist of a thin wafer of silicon crystals arranged in a grid. The limited number of pixels that can be grouped together in the CCD sensor restricts the image resolution. The smaller the pixel size, the better the resolution. The sensors of the intraoral digital system have been improved to pixel sizes of 20-50 μm from up to 70μm. This development has greatly improved the spatial resolution of CCD sensors, because the resolution range, which generates images equivalent to conventional film-based images, is similar to that of the human eye (6 to 10 lp/mm). As a result, the diagnostic image quality is acceptable for clinical practice. Incidentally, the pixel size of CCD-based panoramic system is generally around 100μm.

Direct digital systems with CCD sensors can perform real time imaging; an image is displayed on a monitor within a few seconds. Charge-coupled devices consisting of silicon atoms covalently bonded to adjacent atoms constitute arrays of X-ray- or light-sensitive pixels. In other words, CCDs consist of large numbers of photoelectric cells. Exposure to X-rays or light breaks the bonds and the photoelectric cells generate voltage in proportion to the amount of emission (radiation) energy. The amount of energy required to break the bond is approximately 1.1 V. The CCD charge is read out by transferring the collected charge in each pixel, then it is destroyed, which results in a latent electric image being distributed as a pattern of charges on a matrix. This analog radiographic information is converted to a digital form to be stored in a computer. An analog-to-digital converter transforms the original continuous density range into a set of discrete gray levels. Images generally acquired as 10 to 16 bits in most systems are stored as 8 bits (per pixel) and displayed with 256 shades. If 256 shades of gray are to be represented, the signal from each pixel is converted to the appropriate pixel value from 0 to 255.

Another method of direct digital imaging uses CMOS-based sensors. Compared with CCD-based sensors, one advantage of CMOS technology is the integration of control circuitry, including the A/D converter, directly into the sensor. The image output is from individual pixels and is analog, but it is converted to digital for display on a monitor. Another advantage is that blooming, which resembles allowing too much light through a viewbox and which occurs in CCD sensors due to excess charge leakage into adjacent pixels, can be avoided. This type of sensor has been applied to the most recent Computed Dental Radiography (CDR) (Schick Technologies, Inc., NY, USA) digital intraoral digital system, but it has not yet been incorporated into panoramic and cephalometric imaging equipment.

RADIATION DOSE REDUCTION

Radiation safety is an important issue in dental radiography. The desired amount of information must be obtained by exposing patients to a minimal amount of radiation. Digital intraoral and panoramic radiography generally requires a lower dose per exposure than does conventional dental radiography. Many investigators have compared exposure doses among digital intraoral, conventional intraoral film and digital panoramic radiography in vitro. Table 2 shows the results from some papers on intraoral radiography.

Task-dependent dose reductions of up to 94% with enhancement for individual exposures and 80–90% for standard exposures have been reported from studies of early RVG systems that used CCD sensors. In our study of the RVG-S system, the entry exposure dose for optimal imaging required from one-half to one-third the exposure time of E-speed film, or one-quarter to one-sixth of that needed for D-speed film. The ratios of dose reduc-
tions in various regions of the mouth ranged from 50–65% with respect to E-speed film and 73–76% with respect to D-speed film\(^1\). These findings proved that CCD sensor systems reduced doses by 50–75% of those required for conventional film based methods. The task-dependent dose reduction in digital imaging system strongly relates to the dynamic range of the system.

The dynamic range is narrower in CCD- than in PSP-based systems with a high calibration exposure and conventional film. According to some authors, that of CCD-based digital intraoral radiographic systems reaches a maximum of 12\(\mu\)C/kg, although it is slightly changed by the tube voltage setting\(^1\),\(^3\),\(^9\),\(^16\). Our study of the RVG-S system found that the dynamic range was 8.6 times narrower than that for conventional films\(^20\). The smaller, but acceptable exposure range results from the fact that CCD sensors are more sensitive to X-radiation and reach full saturation at a lower exposure than conventional X-ray film. Additionally, considering reports that the information required to make a clinical diagnosis using a CCD system is similar to that of film, these systems satisfy the ALARA (as low as reasonably achievable) concept\(^2\). In contrast, PSP-based systems including Digora and DenOptix offered a maximal responsible exposure of over 40\(\mu\)C/kg under high calibration exposure\(^22\). The wide dynamic range of PSP-based system has been proven by the fact that an appropriate image quality can be maintained at only 6% of the exposure time needed for E-speed film\(^2\),\(^22\).

CCD-based systems with a narrower dynamic range also have to contend with deteriorated radiation reduction. The smaller sensitive area of most intraoral CCD sensors may require more exposure per investigation, increasing the total dose\(^20\),\(^4\),\(^5\),\(^6\). Because the smaller sensitive area and possible discomfort associated with the CCD sensor make it difficult to position, retakes accompanied by added exposure and re-exposure for the patient may be needed. According to a study by Versteeg et al.\(^60\), 28% of the sensor images obtained from the incisal to the molar region were unacceptable. Similar results were found in an initial study of the RVG system in which the repeat exposure rate was 25%\(^20\). However, assuming that all 25–28% of the original images that are retaken are acceptable, this is still a dose reduction compared with film. A wider dynamic range in PSP-based systems means a large selection range of exposure to X-radiation; conventional film or timely PSP may represent more information but induce overexposures. PSP-based systems accommodate an automatic range control (ARC) mechanism that displays constant image density without being relative to X-ray exposure. The ability to optimize storage-phosphor images means that exposure levels can be low relative to the film. Only a small portion of this wide

<table>
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<th>Authors</th>
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<th>Digital system</th>
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<tr>
<td></td>
<td>D-speed</td>
<td>E-speed</td>
</tr>
<tr>
<td>Soh(^32)</td>
<td>100%</td>
<td>—</td>
</tr>
<tr>
<td>Sanderink(^48)</td>
<td>—</td>
<td>100%</td>
</tr>
<tr>
<td>Wakoh(^62)</td>
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<td>Farman(^10)</td>
<td>100%</td>
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</tr>
<tr>
<td>Brettle(^4)</td>
<td>100%</td>
<td>—</td>
</tr>
<tr>
<td>Huysmans(^22)</td>
<td>100%</td>
<td>—</td>
</tr>
<tr>
<td>Wakoh(^63)</td>
<td>100%</td>
<td>—</td>
</tr>
</tbody>
</table>

**Table 2** Exposure reduction in intraoral digital imaging systems compared with dental X-ray films

(The percentage number in the digital system indicates the exposure rate required when X-ray film required 100%)


\(^\times\): magnified
range, however, is used to acquire an optimal image for a clinical diagnosis. From the viewpoint of radiation protection, whether an ARC should be utilized when a dental clinician gives priority to ALARA concept over image quality is doubtful.

Perhaps, in the near future, a specific dose within a particular dynamic range will be standardized for the diagnosis of specific structures and locations. In addition, the area of sensitivity and the thickness of the receptor may more closely resemble those of traditional film. If these improvements come to pass, then intraoral digital imaging will be established as the modality, because radiation dose will be reduced, image enhancement tools will change contrast and density, and wet processing using chemical will be unnecessary.

Some investigators have studied dose reduction using digital panoramic radiography with a human phantom. The DigiPan and the Orthophos DS receptors based on a solid-state sensor produce satisfactory images with entry exposure savings of approximately 70% and up to 43%, respectively, when compared with a conventional film/rare earth screen combination. A 60% reduction in dose is also claimed by the manufacturer of the DIMAX system.

DIAGNOSTIC STUDY OF CARIES

In previous studies, the accuracy for caries diagnoses for proximal, occlusal, and periodontal bone changes, and periodontal bone changes have been examined. In particular, conventional film radiography, xeroradiography, indirect and direct (semi-direct) digital imaging have promoted radiographic caries diagnosis. Establishment of the validity of digital imaging for caries diagnosis required systematic research into caries.

1. Laboratory experiments

The first studies on the accuracy of caries diagnosis with digital imaging were conducted using the indirect method. This report proved that the sensitivity of caries detection was higher in digitized film images than in either xeroradiographs or film radiographs. In addition, quantitative measurements of caries depth assessed on digitized radiographs were correlated with the histologic depth. Despite these close correlations, no evidence indicated that digital imaging underestimated lesion depth when compared with whitish decalcified histologic zones. Since the first intraoral digital imaging system, RadioVisioGraphy, was introduced in 1989, several investigators have studied caries diagnosis using this type of system. Most of these studies examined the detectability of these systems compared with that of conventional film. When a new diagnostic modality to evaluate dental caries is released, laboratory experiments should initially confirm that the new system is suitable for application to clinical practice. Studies of the first generation of CCD sensors did not identify any significant differences between direct digital systems and digitized film, but paper-print images of this first direct digital system were less accurate than film. Since then, CCD sensors have been substantially improved, and the first dental PSP-based system, DigoRA, became commercially available in 1994. No statistically significant differences were identified among three CCD-based systems and DigoRA in the detection of occlusal and proximal caries lesions. The digital systems did not perform differently from the various film types evaluated by the same observers using the same teeth. A more recent CCD system has also proven comparable to film for interpreting proximal caries. In primary teeth, the PSP-based system storage did not perform differently from film in the detection of cavitated proximal surfaces. In 1997, we also compared the diagnostic accuracy of proximal caries using a first generation CDR system with that of conventional dental X-ray film images using receiver operating characteristics (ROC) analysis. The ROC curve gives the overall performance of a diagnostic system.
and sensitivity at any specificity. We mechanically drilled the proximal surfaces of an extracted tooth and then plugged the defects with dentine powder to simulate proximal caries with low contrast (Fig. 3a). The ROC curve for the CDR image was similar to those of conventional dental X-ray films; the diagnostic accuracy of proximal caries was similar, and this result was also similar to those of previous studies (Fig. 3b, Table 3). However, a problem with the theoretical method of detecting caries was pointed out. Wenzel et al. criticized the relevance to diagnostic image precision of natural dental caries when pseudo- or mechanical caries were generated by using a round bur on extracted teeth. Kang et al. reported that mechanically-produced proximal defects are more easily detected than natural proximal caries because the boundaries between the mechanically-produced defect and the tooth surface are more distinct. The defects were therefore uniform because of this clear boundary. This situation results in a large difference in image contrast, increased detection rate, and improved diagnostic accuracy. Consequently, their study strengthened the support for Wenzels' viewpoint. Wenzel et al. stated that many other experimental designs have been suggested, ranging from the use of another observer or the clinical state of the tooth surface as validation, but such methods should be abandoned. In addition, they stated that the outcome of a new diagnostic method must be held against the true diagnosis that is obtained by a validation or reference method, also called a "gold standard", to test accuracy. That is, only one method can fully resolve this problem: cutting the tooth in sections to visualize demineralization as a discolored area in the dental tissues under a microscope. This is the only validation method that is currently reliable enough for evaluating the efficacy of a new caries diagnostic procedure.
2. Clinical study

The preceding validation method cannot be applied to clinical studies of caries diagnosis, because teeth in situ cannot be sectioned. However, a simulation of the in vivo situation can often be achieved with an in vitro model. A recent study has compared laboratory and clinical results of occlusal and approximal caries diagnosis in the same teeth, comparing pre- with post-extraction teeth. That study found no significant difference in diagnostic accuracy between the two approaches. Therefore, laboratory and clinical diagnosis may closely correspond. Nevertheless, no diagnosis method for caries is yet sufficiently accurate to act as a gold standard for the clinical evaluation of new tests. Clinical studies should focus rather on parameters other than accuracy, such as diagnostic precision or reproducibility, intraobserver and interobserver variation, the consequence to the patient of excluding or establishing a diagnosis, impact on treatment strategy and prognosis, and the radiation dose. Considering that these factors constitute the ultimate evaluation of any new diagnostic method, no studies...
appear to have investigated the effects of digital imaging on overall clinical procedures.

3. Application of image processing tools

Digital imaging systems have several advantages in terms of image processing tools compared with the film-based imaging. Digital radiography is often considered as a replacement for conventional radiography, and this is true to some extent. However, digital radiography offers options that are not attainable with film-based radiography. In this sense, digital radiography is a new method of diagnostic imaging. The lower dose with restrictions on X-ray exposure and the gain of time for image acquisition are key advantages.

Another unique advantage of digital imaging is imaging processing. Caries have been diagnosed using image enhancement inclusive of contrast\(^29,38,51,67\), edge enhancement\(^38,54\), zooming\(^7,54,65\), image compression\(^50\), and image synthesis\(^39,55\). Contrast enhancement seems to be most important prerequisite for predicting caries visibility, although the spatial resolution is lower in most digital systems than in the conventional dental X-ray film. In one study addressing the effects of contrast enhancement of digitized images of low density radiographs, sensitivity increased by approximately 20% without an increase in the number of false positive scores\(^67\). Other studies developed a task-dependent algorithm for approximal caries; accuracy was higher in enhanced PSP-based digital images than in unenhanced digital or film radiographs\(^38\). One study concluded that enhancement may be beneficial for some observers but that selecting the proper procedure is time consuming\(^51\). We also identified an acceptable range of image contrast for the detection of enamel defects by manipulating the contrast and brightness of the CRT display; detection was highly dependent on contrast (Fig. 4)\(^29\). Therefore, if observers find the initial images to be of suboptimal density and contrast, they should be enhanced. The effect of zooming to display various images sizes on the monitor has also been investigated. Møystad et al.\(^27\) reported that the enlargement of digitized film radiographs to examine bite-wing radiography has an upper limit beyond which diagnostic accuracy may be reduced. Our study using a CCD-based system also suggested that magnification has limits in terms of detecting

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**Fig. 4** Effect for caries diagnosis by the combination of the brightness and image contrast on CRT display. 0 at horizontal axis means a default setting of image contrast; the background on monitor is visually a higher density at a minus setting than at the default setting. The bright number also influences the density; the background on the monitor is visually a higher density at a plus setting than at a minus setting.
small holes on proximal surfaces and that excessive magnification reduces the reliability of diagnosing early caries on proximal surfaces (Table 3)\(^{40}\). However, the diagnostic accuracy of the images from which information had been lost by reducing the image size using PSP-based system was comparable with that of conventional film\(^{54}\). These results cannot necessarily be explained by the spatial resolution of the digital sensors and conventional X-ray film. They may be influenced by the observation environment, especially the luminosity of the display-monitor, and by changes in contrast resolution at the time of image magnification and illumination of the viewbox. In other words, spatial resolution may not be a significant factor in diagnosing caries by radiographic means. One study found no relationship between accuracy and image compression for occlusal surfaces; for approximal surfaces, the accuracy was progressively reduced with a difference of 14% between the original and the images compressed by 20%\(^{70}\). Investigations regarding the use of Tuned-Aperture Computed Tomography based on the principle of tomosynthesis generated less explicit results\(^{39,55}\).

Regardless of the more limited resolution, a digital imaging system seems to diagnose caries as well as conventional film radiography, but its diagnostic ability may have several advantages in the future. These are primarily the possibility for image enhancement and a significant reduction in radiation dose to the patient.

CONCLUSION

The movement from analog film towards digital imaging systems is based on a number of advantages of digital imaging systems compared with conventional film radiography: the reduction of the number of retakes because of the possibilities of image processing changing the image contrast and density, the shortening of working time from exposure to image display due to avoiding chemical processing and wet processing errors, the preventing of inferiority of image quality with the development of storage devices. Nevertheless, the gold standard remains analog film. Because of competition from newer digital technologies, manufacturers of X-ray film continue to improve image quality on film at lower radiation doses. Film still has a higher spatial resolution than digital imaging systems, but studies have not demonstrated that this is clinically important. When newer digital receptors are developed in terms of physical factors such as spatial resolution, signal-to-noise ratio, and contrast resolution, when more advanced radiographic methods such as creating three-dimensional displays of dental structure are established, and when the cost of plant and equipment is reduced, diagnostic dentistry will truly enter a totally digital era.

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Reprint requests to:
Dr. Mamoru Wakoh
Department of Oral and Maxillofacial Radiology,
Tokyo Dental College,
1-2-2 Masago, Mihama-ku,
Chiba 261-8502, Japan