Review Article

Digital intra-oral radiography in dentistry. Diagnostic efficacy and dose considerations

Erwin BERKHOUT, DDS[1], Gerard SANDERINK, DDS, PhD,[1]
Paul van der STELT, DDS, PhD[1]

[1]Department of Oral and Maxillofacial Radiology, Academic Centre for Dentistry Amsterdam (ACTA), Amsterdam, The Netherlands

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Introduction

A radiographic image represents the X-ray shadow of patients' internal structures. In conventional film radiography the radiographic film detects, stores and displays the radiographic information. For a long time, radiographic film was the most important medium for the acquisition and archival of diagnostic images. However, since 1987 dental film is no longer unchallenged as the image receptor for intraoral radiography. At that time, the first direct digital system became available for dental practice as an alternative to conventional radiography[1,2]. Some years later, in 1994, the first indirect digital system became available commercially.

In digital radiography X-ray detectors and computers perform the acquisition, archival and display of the radiographic information.

In ten years of time digital radiographic technology has matured and, nowadays, digital radiographic systems are gradually replacing radiographic film. In Western Europe 10 - 20% of the dental practitioners use digital radiographic imaging systems in their dental practice[3,4].

Although film has been an inexpensive and reliable image receptor in dental radiography for a long time, the advantages of digital dental radiography over film include a lower radiation dose, a swift availability of radiographs, the possibility of image enhancement and no need for film processing chemicals.

Many of those advantages are possibilities not found in conventional film-based imaging, which makes the comparison of digital imaging with film-based imaging complicated.

Many review articles and studies describe new systems, applications or possibilities without discussing the comparison to film-based radiography[5-12].

The purpose of this article is to show typical characteristics of digital radiography and compare them to conventional imaging, and furthermore to discuss the additional possibilities of digital radiography.

First we will discuss the two technologies for digital image acquisition; secondly the image quality of the digital systems is discussed on the basis of the various diagnostic tasks. Image enhancement and dose aspects, will be brought up as well.

Systems

Analogue vs. Digital

Conventional radiography is based on the interaction of X-ray photons with electrons of silver bromide crystals in the film emulsion, production of a latent image, and subsequently chemical processing that transforms the latent image into a visible one[13]. The film-radiograph may have a continuous density distribution, limited only by the maximum and minimum values of density (black and white). Each optical density in between the minimum and maximum is related to the amount of light that can pass trough the film at a certain site. Based on the continuous density scale film-based images are called analogue images.

A digital image, on the other hand, consists of a matrix of cells having a range of various gray levels on the computer monitor. The X-ray intensity is translated into discrete values, called gray levels. The number of gray levels normally used is 256, which is equivalent to 8 bit per pixel (2^8=256). This range of gray levels is called the *contrast resolution*.

The contrast resolution of the human eye is usually between 50 and 100 gray levels, so the number of 256 gray levels in a digital image is sufficiently enough for the human visual system to simulate a continuous gray scale.

In digital images gray values are found only at well-defined spatial positions, called pixels (picture elements). The number of pixels per inch or centimeter defines the so-called *spatial resolution*. The more pixels are arranged in a matrix, the better the quality of the image that is captured. The limited number of pixels that can be grouped together restricts the digital spatial image resolution in solid-state systems. In phosphor plate systems the accuracy of the laser scanner and the scattering of laser light within the phosphor layer limit the spatial resolution[14].

The smallest detectable object depends on the spatial resolution as well as the contrast resolution[15].

In the literature the terminology to discriminate between several kinds of 'digital' systems is confusing. Most authors call digital sensor systems that are attached to the computer with a wire a direct system. However, phosphor plate systems are also called direct systems, because of the direct acquisition of the digital image. Other authors call phosphor plate systems 'indirect systems' because of the extra action that needs to be done to scan the plate in the laser scanner. Again others have found a compromise in the term 'semi direct systems'. The digitization of a film radiograph to a digital image using a flatbed scanner or video camera is mostly called the truly 'indirect system' [16]. Terminology that causes less confusion is 'solid-state systems' for sensor systems that are attached to the computer with a wire and on the other hand 'phosphor plate systems'.

Solid-state systems

Solid-state systems include an electronic X-ray sensor, a digital interface card, a computer with a screen monitor and software. Current systems are mostly based on personal computer (PC) technology and require a Pentium II processor (or higher), sufficient internal memory (at least 128 Mb), a SVGA graphics card and a high-resolution monitor (1024 × 768 pixels) [17].

Solid-state sensors are either a charge-coupled device (CCD) or a complementary metal oxide semiconductor active pixel sensor (CMOS-APS).

A CCD is made up of arrays of X-ray-sensitive or light-sensitive pixels. The size of one pixel is approximately 40 μm × 40 μm, some CCDs are even as small as 20 μm × 20 μm[18]. The pixels, in fact photoelectric cells, generate voltage in proportion to the amount of X-rays or light striking them. This charge is transferred (coupled) to a readout amplifier for image display. Intra-oral CCD-sensors fall into two categories: the fiber optically coupled sensors and the directly exposed sensors. Fiber optically coupled sensors use a scintillation (intensifying) screen coupled to a CCD. Light photons, that are the result of the interaction of X-rays with the screen, are transmitted by the fibers to the CCD. The directly exposed CCDs capture the image directly without the intermediate scintillation layer[15].

In contrast to CCD sensors CMOS-APS sensors use an active pixel technology. This technology provides design integration what makes the sensor less expensive to manufacture and may improve the reliability and lifespan of the sensor[13]. However, CMOS-APS sensors have more fixed pattern noise and a smaller active area for image acquisiation[17].

With respect to the physical performance of the different sensor systems, it was found that grey level values in images from solid-state systems decrease faster with increasing exposure than in images from phosphor plate systems, resulting in darker images and deterioration of the image caused by blooming effects. Noise increases with increased exposure for both solid-state and phosphor plate systems. Solid-state systems reach their highest contrast index at lower doses than the phosphor plate systems. Solid-state systems have better resolving power due to higher contrast and smaller pixel sizes than phosphor plate systems[19].

Phosphor plate systems

Storage Phosphor Plate systems (SPP), also called Photostimulable Phosphor systems (PSP), temporarily store the radiation energy of the latent X-ray image on a sensitive plate. By stimulating the phosphor on the plate with a laser-beam in a readout-scanner, the energy stored on the plate is emitted as light. The intensity of the light in a given area is linearly proportional to the amount of X-ray energy that has been absorbed. The scanner measures the emitted light. The measurements are displayed on the monitor as a digital image[14, 20].

The phosphor plate is able to store the X-ray energy for many days; however, it is best to read them as soon as possible. In one day an exposed imaging plate, stored in a dark environment and enclosed in a protective bag, loses half of its stored energy[21]. After read-out flooding the plate with bright light erases any residual energy. The phosphor plates are reusable, and therefore should be enclosed in an infection control barrier before placement in the mouth of the patient. The image plates cannot be sterilized.

The image size and the fact that the plates are cordless, in contrast to solid-sate systems, make phosphor plate systems and conventional film very similar with respect to the manipulation of the plates in the mouth of the patient.

The pixel size of phosphor plate systems is depending on the focal spot of the laser-beam and the accuracy of the movement of the plate or laser-beam in the scanner[21]. The pixel size of the first Soredex Digora® phosphor plate system (Soredex-Orion Co., Helsinki, Finland) (white plates) is 70 μm[22]. The new version, the Digora FMX system produces an image of 628 × 466 pixels for the same active area, resulting in a pixel size of 64 μm.

The development of digital radiographic systems is still going on. Especially for solid-state systems this development is going rapidly. In the last two years, many manufactures have developed high-resolution sensors that are producing 12-bit data output, giving 1024 gray levels. Some of those systems present the radiograph as a 12-bit image; others convert the 12-bit data to an 8-bit image on the monitor.

Since the development is going rapidly, it is important for researchers to clarify in scientific publications which system and which version of that system they used. Also the version of the software of the system should be mentioned.

Unfortunately, at this moment many authors do not clearly describe the system used in their studies[22, 23, 58].

Diagnostic efficacy

Cariology

Carious lesions have traditionally been detected by a clinical examination supplemented by radiography. The use of radiographs increases the number of lesions detected by clinical examination[24]. However, numerous studies have demonstrated the tendency for radiographic diagnosis to underestimate the severity of the lesions[25-27].

New imaging modalities, such as digital radiography, should at least have an accuracy that is comparable with that of dental films.

A study of the first digital system for intraoral radiography (the Trophy RadioVisioGraphy) showed no statistically significant difference with conventional film and digitized radiographs for the detection of dentinal caries in occlusal surfaces of noncavitated extracted teeth[28].

Meanwhile many more studies have shown that solid-state sensors (CCD as well as CMOS-APS) and most phosphor plate systems performed as well as E-speed film in diagnostic efficacy for proximal caries[23, 29-33]. Two studies investigating the CD-dent phosphor plate system (previously Digident, Orex, Yokneam, Israel), showed that this system is not as accurate as the other digital radiographic systems. Observers ranked the system inferior[34, 35].

In most cases the exposure time for the digital radiographic systems was set to 10-50% of that of E-speed film. All studies mentioned were performed using a common dental tube potential (65 or 70 kVp). Research has shown that a variation of tube potential has a negligible effect on proximal caries diagnosis using X-ray film[36]. However, it has never been shown that this is also true for digital radiography. More research is needed.

In vivo research in caries radiodiagnosis is not regularly performed, mainly due to the difficulty of obtaining a 'gold standard'. Hintze & Wenzel found no significant difference in the diagnostic accuracy of film radiographs obtained both *in vivo* and *in vitro* of the same third molars for the detection of occlusal and approximal caries[37]. It was concluded that the results from good laboratory studies could be transferred to the clinical situation. However, an *in vivo* study by Versteeg *et al.* comparing the Digora phosphor plate system with E-speed film for the detection of proximal caries showed that the phosphor plate system underestimated caries depth in comparison with film-based images[38].

For the Digora system Møystad *et al.* studied the accuracy of proximal caries detection using original and digitally enhanced storage phosphor images and E-speed film[39]. For both enamel and dentin lesions the enhanced images performed significantly better than the original digital radiographs and film. No significant difference was found between the original digital radiographs and film. Another study showed that a caries-specific enhancement procedure (the so-called Oslo enhancement filter) of storage phosphor images significantly improved the accuracy of caries depth assessment in the outer half of the enamel compared with E-speed film, and moreover, it reduced interobserver variability. For caries lesions penetrating beyond the outer half of the enamel no significant differences were found[40].

In addition to the positive effect of image enhancement on diagnostic efficacy, also magnification seems to have a significant influence on observer performance in the detection of proximal caries. However, there is an upper limit of about 15x magnification beyond which diagnostic accuracy may be reduced[41, 42].

Endodontology

Manufacturers of digital radiographic systems, notably solid-state systems, advocate the use of their products particularly in determining root canal length during endodontic treatment. In those cases, the rapid image acquisition is the selling argument.

Several studies have been performed on the diagnostic efficacy of digital radiographic systems with respect to determining the length of the root canal or the visibility of endodontic files[43-46]. Those studies concluded that the digital systems used in the studies provided comparable results to conventional film-based radiography in determining the length of the root or root canal.

However, Shearer *et al.* were less satisfied with the performance of digital systems in determining root canal length. Three phosphor plate systems (Digora, CD-dent and DenOptix) (DenOptix, Dentsply-Gendex, Milan, Italy) and E-speed film were compared with respect to the imaging of root canals[47]. For this task a good low contrast distinction is a requisite. It was concluded that the length of the root canal is better visible on conventional film than on the three phosphor plate systems. In the opinion of the authors this might be of clinical relevance.

Another important diagnostic task in endodontic radiography is determining the length of the endodontic file in the root canal. In 1994, Sanderink et al compared five solid-state systems with Ektaspeed film on the visibility of endodontic files. It was concluded that the digital systems performed equally to film with the use of file size 15, but film outperformed the digital systems with the use of file size 10.48 Also Versteeg *et al.* (1997) and Lozano *et al.* (2002) concluded from their studies that digital systems and conventional film are comparable with respect to the visibility of endodontic files when using file size 15 or higher[49, 50]. Vandre *et al.* studied six digital radiographic systems and film on the accuracy for endodontic measurement[51]. All digital systems gave greater mean measurement errors than film. However, three of the studied digital systems (Dexis, CDR and RVG-4) (Dexis, Provision Dental Systems, Palo Alto, CA, USA), (CDR, Schick Industries, Long Island City, NY, USA), (RVG-4, Trophy Radiologie S.A., Croissy-Beaubourg, France) did not differ significantly from film. The other three digital systems (Digora, Sens-A-Ray and Visualix-2) (Sens-A-Ray, Dent-X, Regam Medical Systems, Sundsvall, Sweden), (Visualix, Dentsply, Milan, Italy) did differ significantly from film. Apparently, the researchers judged the differences as relatively small, because they concluded that digital systems closely approximate film in their accuracy when used for endodontic measurement. Cederberg *et al.* (1998) and Eikenberg and Vandre (2000) were even more enthusiastic about digital radiographic systems[52, 53]. They both concluded from their studies that measuring the distance between file tip and apical foramen was statistically significantly more accurate on digital radiographs than on film, although this was thought to be of no *clinical* benefit.

Periapical lesions

Several studies have evaluated the efficacy of digital radiographic systems in the detection of periapical lesions. Holtzmann *et al.* (1998) compared D-speed film, E-speed film and the Digora phosphor plate system with respect to the detection of periradiculair pathosis[54]. Radiographs were made of 100 cadaver jaws, which subsequently were sectioned for histologic examination. The observer performance was compared with the true histologic findings. It was determined that D-speed film, E-speed film and the phosphor plate system were equivalent diagnostic imaging modalities with regard to the detection of periradicular bone resorption. Also Paurazas *et al.* (2000) compared three systems, E-speed film, a CCD system, and a CMOS-APS system[55]. She did not mention the make and type of the systems. Periapical lesions were created in the cortical and trabecular bone of 10 dried human mandibles. Lesion detection by seven observers occurred with significantly greater accuracy in cortical bone than in trabecular bone. Nevertheless, no differences were found in the detection of the lesions between film, CCD, and CMOS-APS systems. Kullendorff *et al.* studied the diagnostic accuracy of digital radiographs for the detection of periapical lesions too[56]. They also drew the conclusion that the quality of digital images is comparable to that of E-speed film for the detection of periapical bone lesions.

On the other hand, a study by Wallace *et al.* (2001) showed that conventional film-based radiography was better for the detection of periapical lesions[57]. The study compared Ektaspeed Plus film (Eastman Kodak, Rochester, NY, USA), the Digora phosphor plate system, and the Schick-CDR solid-state sensor. Lesions were simulated in the periapical areas of human mandibular sections and imaged using the three systems. Ektaspeed Plus film outperformed both digital systems in sensitivity and specificity for the detection of periapical lesions.

Periodontology

The diagnostic efficacy of digital imaging has also been explored with regard to periodontal lesions. Nair *et al.* evaluated the accuracy of alveolar crestal bone detection in a comparison of original and enhanced Sidexis digital images (Sirona Dental Systems GmbH, Bensheim, Germany) with Ektaspeed Plus film[58]. More than 100 proximal and furcal areas in the anterior and posterior areas of the mandible and maxilla of three human skull phantoms were imaged. Five observers assessed all images for the presence or absence of crestal bone loss. It was concluded that the Sidexis digital images were not significantly different from Ektaspeed Plus film for crestal bone evaluation.

Eikholz *et al.* compared linear measurements of interproximal bone loss on digitized radiographic images after application of different filters to the gold standard of intrasurgical measurements[59]. Neither the measurement of the distance from the cemento-enamel junction to the alveolar crest on the unchanged images nor assessments with any of the filters revealed significant differences from the gold standard. Therefore, it was concluded that all radiographic assessments on the digitized images came close to the intrasurgical gold standard.

The effect of image enhancement on diagnostic efficacy

Digital acquisition of radiographs enables digital image enhancement. In diagnostic imaging, the objective of image processing is to make relevant information more evident by creating images that are better suited for human visual perception[60]. The same image may be used for various diagnostic tasks by adjusting the image characteristics. For instance a radiograph should be lighter for detection of marginal bone loss, whereas caries detection requires a darker image with increased contrast. Smoothing reduces the image noise, at the expense of a decrease in resolution. High-pass spatial filtering (hardening) enhances edges thus returning a crisper image, but with more noise[15]. All systems for digital imaging offer one or more types of image enhancement methods, causing a great variety of techniques among all systems. This made Lehmann *et al.* conclude from their study that standardized terminology and increased functionality of image processing should be offered to the dental profession[61].

A study by Borg (1999) has shown that the images of phosphor plate systems need some enhancement to improve the diagnostic performance[19]. This is because the resolving power of the phosphor plate systems improves when the images are enhanced. The software of phosphor plate systems usually applies the systems' default greyscale adjustment to the images to perform the needed enhancement. However, noise in phosphor plate images will increase to a certain extent when image enhancement is applied. When exposure increases noise decreases.

Several studies have shown that digital contrast enhancement and filtering may increase diagnostic accuracy[39, 62]. Svanaes *et al.* conducted a study on image enhancement of phosphor plate images[40]. As mentioned in the paragraph on cariology of this article, it was concluded that digital image enhancement of storage phosphor images significantly improved the accuracy of caries depth assessment in the outer half of the enamel compared to Ektaspeed film. Also Shrout *et al.* concluded from their study on the effect of image enhancement that it improved the validity of caries assessment[63].

However, the results of many studies on image enhancement are rather divided. Even deterioration of diagnostic accuracy by digital image enhancement has been reported[64]. Kullendorff *et al.* (1997) performed a clinical study in which a Visualix/VIXA solid-state sensor was compared with Ektaspeed film for the detection of periapical lesions. Conventional periapical radiographs as well as digital periapical radiographs were taken of 50 patients. Observer performance was assessed of conventional radiography and of digital radiography; the latter with and without image processing and ROC-analysis was applied. Az values showed no significant differences between conventional radiographs and original digital images. The enhanced digital images performed significantly worse for the detection of periapical lesions. Also Farman *et al.* did a clinical study on the accuracy of the assessment of intraosseous lesion dimensions[65]. Ektaspeed Plus radiographs and the Visualix-2 solid-state system in unenhanced, contrast-stretched and equalized modes were compared. When image equalization was applied, the measurements were closest to the "gold standard". The contrast-stretched and unenhanced measurements were less accurate; conventional film was consistently the least accurate.

Kullendorff *et al.* made a comparison between original digital images and images processed with different enhancement procedures[66]. The results show that basic image processing, which is altering of contrast and brightness, are after all the most effective. More complicated processing procedures have less effect on the diagnostic accuracy. It was concluded that image processing of digital images of high quality had a limited effect on the diagnostic accuracy.

Wolf *et al.* performed a study on the efficacy of image enhancement in periodontology[67]. The aim was to assess the reproducibility and validity of linear measurements of interproximal bone loss on digitized radiographic images after application of different filters. It was concluded that the chosen filters failed to result in statistically significantly more reproducible or valid measurements when compared to the digitized but unchanged images. Nair *et al.* and Eickholz *et al.* drew the same conclusion from their studies on the accuracy of alvealor crest bone detection[58, 59].

We conclude that due to the subjectivity and task-dependence of image enhancement it can be expected that general use of such enhancement techniques may not lead to improvement of diagnostic efficacy. Only for caries diagnostics most studies concluded that enhancement improves the detection of small lesions. In general, the optimal image enhancement technique for a given diagnostic task is a function of the digital radiographic system used, the diagnostic task, characteristics of the display medium, and the human observer[68].

Subjective image quality

Subjective opinions on the image quality of digital radiographs by experienced dental radiologists and dentists are another approach to evaluate the utility of the digital systems tested. Already in 1977, Thornbury *et al.* proposed a methodology for comparison of quality of radiologic images based on radiologists' subjective judgements[69]. Using this methodology, Vucich suggested subjective evaluation of the degree to which pre-defined anatomical landmarks are clearly visualised[70]. Kundel suggested a similar approach to define image quality because of his observation that the role of the observer performance in the evaluation of diagnostic image quality has been underemphasized compared with the technical aspects[71]. It is assumed that such a subjective evaluation will also include the effects of the physical parameters of the imaging system influencing the diagnostically important aspects of image quality[72].

An advantage of this approach is that the image quality of a radiograph can be evaluated for a variety of diagnostic tasks. So a situation is created that is comparable to the general dental practice.

Recently, in two studies several digital radiographic systems were compared using subjective image quality. Kitagawa *et al.* compared three intra-oral phosphor plate systems, the Digora system, the DenOptix system with two different types of phosphor plates, and the DigiDent (CD-Dent) system[34]. It was concluded that DenOptix combined with BAS300 phosphor plates (Fuji Photo Film Co., Tokyo, Japan) gave the best overall image quality, whereas the Digora images were considered to be the best for demonstrating gingival soft tissues.

Borg *et al.* compared four solid-state systems and two phosphor plate systems[72]. It was concluded that the Schick-CDR CCD and APS solid-state sensors had the best image quality, but also the narrowest exposure range. Both phosphor plate systems (Digora and DenOptix) provided a clinically acceptable image quality over a wide exposure range, and both Visualix systems had the lowest image quality. In addition, this study as well concluded that image enhancement did not generally improve image quality.

Farman et al compared the subjective image quality of the Visualix-2 solid-state system to Ektaspeed Plus film in an *in vivo* study[65]. The subjective preference of the observers placed enhanced Visualix-2 images above film radiographs, but unenhanced Visualix-2 images were rated worse than film radiographs.

The diagnostic efficacy of digital radiographic systems as determined in laboratory studies and a few clinical studies seems to be clinically acceptable and useful. Therefore, digital radiographs can be used diagnostically without compromising the interests of the patient, and subsequently used for further studies on the diagnostic performance of these systems. However, histological validation of the findings is usually not possible in clinical studies. Consequently, another manner of comparing the images should be found. The choice of the validation method is crucial in this respect. Hintze and Wenzel concluded that the diagnostic efficacy as a measurement of system performance was strongly influenced by the validation method[73].

From another study on the comparison of microscopy and radiography as gold standards in radiographic caries diagnosis, Hintze and Wenzel claimed that results obtained using observers' scores from the radiographs, as validation for the presence of caries, might mislead the clinician[74].

When radiographic validation misleads the clinician and histological validation is not possible in an *in vivo* study, subjective image quality assessment seems to be a useful method to compare digital radiographic systems mutually and with film in a clinical setting.

Dose considerations

Radiation safety is an important issue in dental radiography. The desired amount of information must be obtained with the smallest possible amount of radiation. The dose reduction obtained by digital radiography as compared with film-based radiography has been emphasized since the introduction of digital imaging in dental radiography in the 1980s. It is questionable, however, if the dose reduction is as large as has been suggested by manufacturers and some users. At first, the dose should be compared with E-speed or even F-speed film. The use of D-speed film as the reference as used in many publications overrates the dose reduction[46].

Yet, compared to E-speed film in laboratory conditions, digital intraoral radiography requires a dose per exposure that is generally lower than that for conventional film-based radiography[14, 31, 62, 75–78]. A survey on the use of digital radiography in general dental practice in Norway showed that the mean reduction in exposure time was 55%[79]. The expectation that users with small size digital sensors would collimate their radiation field could not be confirmed.

Moreover, the patient dose is determined not only by the amount of radiation per exposure, but also by the number of radiographs taken. A recent study shows that the total number of radiographs taken by dentists using digital radiography was significantly larger than the number of radiographs taken by film-users[80]. The number of radiographs taken by dentists using solid-state systems compared to film-users increased by nearly 50%. Phosphor plate users took 32% more radiographs. Several factors do explain this increase. According to the answers of the dentists in the survey, better diagnostics was the main reason when taking more radiographs. However, a study by Versteeg *et al.* also showed that positioning errors occurred more often in digital radiography than in film-based radiography[81]. Because of the stiffness of the digital sensors the positioning in the mouth of the patient is significantly more difficult than positioning film, and more uncomfortable for the patient[3, 82]. This also is an important factor of extra radiographs to be taken. Another reason for retakes might be the relatively narrow dynamic range of solid-state systems. Blooming effects will deteriorate images from solid-state systems at lower doses than burn-out effects deteriorated conventional radiographs or images from a phosphor plate system[19, 75].

In conclusion, digital intra-oral radiography is a well-accepted diagnostic tool in dental practice. However, some of the claims made by manufacturers of digital systems, are not valid to their full extent. For instance, the dose reduction per exposure is real, but it is still to be determined what the actual dose reduction is because of the fact that dentists tend to make more radiographs when using a digital system. For many dentists, digital radiography is a new technology. This requires additional training before the quality of the imaging procedure in hands of the dentist and the members of his team will match their experience gained in conventional radiography.

Other aspects, such as image enhancement and task specific image optimization, still need further research before the patient can fully benefit from this added value of digital systems.

It is nevertheless clear from many studies that the diagnostic performance of digital radiography is at least comparable to or even better than that of conventional radiography. Digital radiography is a helpful tool in clinical practice.

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Reprint requests to:
Erwin BERKHOUT
ACTA-Department of Oral Radiology
Louwesweg 1 1066 EA Amsterdam The Netherlands
Tel: +31-20-5188261 Fax: +31-20-5188480
E-mail: e.berkhout@acta.nl