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ORIGINAL ARTICLE

# Detection of non-cavitated approximal caries lesions in digital images from seven solid-state receptors with particular focus on task-specific enhancement filters. An ex vivo study in human teeth

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**Abstract** The aim of this study was to compare detection of non-cavitated approximal caries lesions in images from seven solid-state intraoral digital receptors, with particular focus on two task-specific enhancement filters. One hundred and sixty approximal non-cavitated surfaces were radiographed under standardized conditions using the following seven intraoral solid-state digital receptors: two CMOS systems, Schick CDR-APS, and Kodak RVGui; and five CCD systems: Visualix, VistaRay, Dixi2, Sidexis, and Dr. Suni Plus. The Kodak RVGui digital images were captured with two task-specific, predefined enhancement filters ("dento-enamel" and "periodontal"). Eight observers examined the digital images for the presence or absence of approximal carious lesions. The teeth were subsequently sectioned for histological analysis, which served as the "gold standard" for the radiographic examination and allowed for a calculation of sensitivity, specificity, and overall accuracy. Both RVG modalities obtained the highest sensitivity values, which were significantly higher than with Visualix, Sidexis, and VistaRay images (all $P \leq 0.03$). The RVG "periodontal" images also had a higher accuracy than Dixi2, Dr. Suni Plus, and CDR-APS ($P \leq 0.05$). The RVG modalities also showed the largest observer variation, and their high sensitivities were mainly due to one observer. The sensitivity for VistaRay images was the lowest of all modalities and significantly lower than almost all the other digital systems ($P \leq 0.02$; except for Visualix). Besides, Visualix images had lower sensitivity than CDR-APS, Dixi2, and Dr. Suni Plus images ($P \leq 0.003$). On the other hand, the two RVGui image types showed the lowest mean specificity values. For overall accuracy, the differences among the modalities were non-significant ($P > 0.05$).

**Keywords** Radiography · Digital radiography · Image processing · Ex vivo · Dental caries

## Introduction

Direct digital solid-state radiography systems for recording of intraoral radiographs have been widely marketed to general dental practice since the end of the 1980s [2]. The solid-state receptor consists of a charge-coupled device (CCD) or a complementary metal oxide silicon (CMOS) chip sensitive to light, and a scintillator layer that converts X-radiation to light [7]. Digital images generated with these receptors have been shown to possess a diagnostic accuracy comparable to conventional film radiography for approximal caries detection in most previous studies [1, 4, 6, 11, 17, 20–22, 28]. Solid-state sensors undergo, however, continuous changes, and no studies have compared accuracy for caries detection among the most widely used and recent sensor versions.

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Post-processing methods, such as histogram equalization, noise reduction, and contrast and brightness adjustments, may be used in connection with detection of caries. Image enhancement procedures may accent particular structures or borderlines in the image. Filtering is one such procedure that uses mathematical algorithms in order to enhance or reduce specific features in the image. The use of a filter might compensate for losses in image quality caused by underexposure or noise. Consequently, the use of digital filters may be accompanied by a reduction in exposure dose [12]. Predefined, task-dependent enhancement routines may be of interest to the dental practitioner; however, few software programs offer this option. Studies on the effect of specifically developed filters on approximal caries detection are scarce. One study found no differences in accuracy of occlusal caries lesion detection between RVGui (Trophy Radiologie) original images and the same images processed with a sharpen filter or with pseudo-colors [13]. One study on Sidexis (Sirona Dental Systems GmbH) images found no differences between filtered or inverted images and their originals [12], while another study found that inverted images had lower accuracy for detection of approximal dentine lesions [8]. A third study showed that enhanced images from the Dixi (Planmeca Oy) system had a higher accuracy than un-enhanced images [14]. One research group has developed and evaluated a caries-specific algorithm and found that images pre-enhanced with this filter had the same diagnostic accuracy as when the same images were individually enhanced, but there was less observer variation with the pre-enhanced images [15, 19].

The aim of this study was therefore to compare detection of non-cavitated approximal caries lesions in digital images from seven solid-state intraoral digital receptors, with particular focus on two task-specific enhancement filters.

## Materials and methods

Non-cavitated extracted human permanent teeth (20 canines, 40 premolars, and 40 molars) with both sound and carious approximal surfaces were used in this study. On visual examination, the carious surfaces had varying degrees of demineralization appearing as chalky white or brownish discoloration areas. The teeth were mounted in 20 blocks of silicone, disregarding the surface status, with four test teeth (two premolars and two molars) and one non-test canine in each block. The teeth were placed in an anatomical position from the apex to the cemento-enamel junction with approximal surfaces in contact. The non-test tooth was placed at the beginning of the block to secure approximal contact for the first test tooth.

In the present study, each test tooth in each block was radiographed separately using a Gendex DC X-ray unit (Gendex, Des Plaines, IL, USA) with rectangular collimation operating at 65 kVp, 10 mA, and 32 cm focus-film distance. To obtain identical irradiation geometry for the solid-state detectors and the conventional film, the blocks of silicone and the image receptor were stabilized on a positioning jig to provide a central beam orientation, 22 mm tooth–receptor distance, and the same target-to-receptor distance. A 12-mm acrylic plate was placed between the tube extension and the teeth to simulate soft tissue. The teeth were radiographed with the following seven intraoral solid-state digital sensor systems: two CMOS systems, Schick CDR-APS (Schick Technologies Inc., Long Island City, NY, USA) and Kodak RVG, RVGui (Eastman Kodak, Rochester, NY, USA); and five CCD systems: Visualix (Gendex, Milan, Italy), VistaRay (Dürr Dental, Bietigheim-Bissingen, Germany), Dixi2 (Planmeca Oy, Helsinki, Finland), Sidexis (Sirona, Bensheim, Germany), and Dr. Suni Plus (Suni Medical Imaging Inc., CA, USA). The digital system specifications are shown in Table 1. The RVGui system provides the following three types of diagnostic modes: "dento-enamel" mode for caries detection, "periodontal" mode for assessment of alveolar bone, and "endodontic" mode for the assessment of the root canals and periapical bone. In this study, the exposures with the RVG sensor were performed twice capturing images in the "dento-enamel" mode (Fig. 1), which intends to provide high-contrast images, and in the "periodontal" mode, which

**Table 1** The digital system specifications provided by the manufacturers

| System name | Manufacturer | Pixel size (μm) | Technology | Software for image capture |
|---|---|---|---|---|
| CDR-APS | Schick Technologies Inc. | 40×40 | CMOS | CDR for DICOM Windows 3.0.1 |
| Kodak RVGui | Eastman Kodak | 18.5×18.5 | CMOS | Kodak Windows 6.0.1 |
| Visualix | Gendex | 22×22 | CCD | VixWin 2000 |
| VistaRay | Dürr Dental | 22×22 | CCD | DBSWIN |
| Dixi2 | Planmeca Oy | 19×19 | CCD | Dimaxis Pro 3.01 |
| Sidexis | Sirona | 39×39 | CCD | Sirona Sidexis XG |
| Dr. Suni Plus | Suni Medical Imaging Inc. | 22.5×22.5 | CCD | Prof. Suni software |

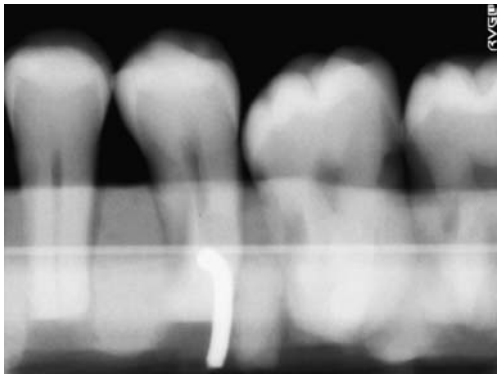

**Fig. 1** Radiographic image using "dento-enamel" filter showing high contrast

intends to provide low-contrast images (Fig. 2). Therefore, there were eight radiographic modalities included in the test.

Before the study, two observers in consensus and blind selected for each receptor the image that had an acceptable quality for caries detection, from among images obtained of one tooth block using several exposure times (0.18, 0.22, 0.26, 0.30, 0.34, 0.42, and 0.50 s). If no difference in quality between two images with different exposure times could be subjectively determined, the image taken with the lowest exposure time was selected. The exposure times were as follows: Schick CDR-APS: 0.26 s (molars) and 0.22 s (premolars); Kodak RVG: 0.26 s (molars) and 0.18 s (premolars); Visualix: 0.22 s (molars) and 0.18 s (premolars); VistaRay: 0.26 s (molars) and 0.22 s (premolars); Dixi2: 0.26 s (molars) and 0.22 s (premolars); Sidexis: 0.22 s (molars) and 0.18 s (premolars); and Dr. Suni Plus: 0.26 s (molars) and 0.26 s (premolars).

The digital images from all systems were saved in non-compressed file format (tagged image file format, TIFF). The image characteristics of each radiographic modality are shown in Table 2. The digital images were coded to hide their origin and displayed in a random order and full size (1:1) on a 17-in. CRT monitor, 1,024×768 pixels, using the general program CaScO software (Erik Gotfredsen, School of Dentistry, University of Aarhus, Denmark) with facilities to adjust contrast, brightness, gamma curve function, and to zoom as the observer pleased. If image resolution exceeded that of the monitor, the image was still displayed in 1:1 (full size), and a scroll bar allowed the observer to view separate parts of the image. The scroll bar was as default placed so that the crown of the image was visible on the monitor when the image was opened. The observations took place in a quiet and windowless room with subdued ambient lighting. Eight observers, with at least 6 years of experience in radiographic caries diagnosis, recorded approximal caries lesions on a 5-point rank scale: 1 = caries definitely absent, 2 = caries probably absent, 3 = unsure if present or absent, 4 = caries probably present, and 5 = caries definitely present. The viewing session order for the observers was randomized, and a period of at least 1 day separated the sessions.

**Fig. 2** Radiographic image using "periodontal" filter showing low contrast

For the validation of the true presence of caries, each test tooth was completely embedded in acrylic (Vipcril, Vipi, São Paulo, Brazil) and serially sectioned in the mesio-distal direction using a Low Speed Diamond Nheel Exakt saw (South Bay Technology Inc., CA, USA) with a 200-μm diamond band into 700-μm-thick sections. The tooth sections were glued on microscope glasses using transparent varnish. Two observers individually validated the tooth sections using a light microscope at ×12–16 magnification. Approximal caries lesions, defined as an opaque-white demineralization or brownish discoloration observed in the approximal surface, was scored on a scale from 0 to 2, where 0 = no lesion, 1 = caries in enamel, and 2 = caries ≤1/3 into dentine. The highest score from the various sections of an approximal surface was defined as the true status for the assessed surface and used as "gold standard" for the radiographic scores. In case the observers' ratings varied, they performed a joint assessment to establish agreement.

## Data analysis

The 5-point rank scale for the radiographic examination was dichotomized and cut off between scores 3 and 4; scores 1, 2, and 3 defined as sound surface and scores 4 and 5 defined as surface with lesion. There were few scores 3 among the recordings (mean=9%). For each observer with each radiographic modality, their scores were compared with the "gold standard" to obtain the sensitivity, specificity, and overall accuracy (percentage of correct scores). The difference in sensitivity, specificity, and accuracy between the eight modalities was estimated by analyzing the binary data assuming additive effects of observer and method in a generalized linear model using identity link. The correlation within surfaces was adjusted for by applying robust standard errors. The significance level was set to $P<0.05$.

**Table 2** Image characteristics of each digital radiographic modality

| System name | Bit | File format | Width (pixel) | Height (pixel) | Width (cm) | Height (cm) | Ppi | Ppcm | File size (kb) |
|---|---|---|---|---|---|---|---|---|---|
| CDR-APS | 8 | Tiff | 900 | 640 | 3.60 | 2.56 | 635 | 250 | 564 |
| RVGui-enamel | 8 | Tiff | 1,600 | 1,200 | 2.96 | 2.22 | 1,372 | 540 | 1,879 |
| RVGui-perio | 8 | Tiff | 1,600 | 1,200 | 2.96 | 2.22 | 1,372 | 540 | 1,879 |
| Visualix | 8 | Tiff | 1,640 | 1,250 | 3.61 | 2.75 | 1,153 | 454 | 2.004 |
| VistaRay | 8 | Tiff | 1,612 | 1,232 | 4.05 | 3.10 | 1,011 | 398 | Up to 1.968 |
| Dixi2 | 8 | Tiff | 972 | 682 | 3.69 | 2.59 | 668 | 263 | 647 |
| Sidexis | 8 | Tiff | 872 | 676 | 3.40 | 2.64 | 651 | 256 | 576 |
| Dr. Suni Plus | 8 | Tiff LZW | 800 | 578 | 3.60 | 2.60 | 564 | 222 | Up to 430 |

## Results

The true status of the 160 approximal surfaces according to histological examination is presented in Table 3.

Figure 3 shows the sensitivities and specificities for the eight observers. The observers diagnosed quite differently; in particular did one observer score many lesions with the RVG modalities and with Dixi2 (large circle) and therefore had a high sensitivity and a low specificity with these systems, while another observer did the opposite (large square) and scored almost no lesions with any system, with a very low sensitivity and 100% specificity as the result.

The mean sensitivity, specificity, and overall accuracy for each radiographic modality are shown in Table 4. The two types of RVGui images captured with the specific filters ("dento-enamel" and "periodontal") showed almost identical values for all three parameters. The two RVG modalities obtained the highest sensitivity values, which were significantly higher than with Visualix, Sidexis, and VistaRay images (all $P \leq 0.03$). The RVG "periodontal" images had, moreover, a higher accuracy than Dixi2, Dr. Suni Plus, and CDR-APS ($P \leq 0.05$). This finding may be attributed mainly to one observer, who scored extremely many lesions with the RVG modalities (Fig. 3, dotted line). It may also be seen from Fig. 3 that the RVG modalities in general had the most observer variation. The sensitivity for VistaRay images was the lowest of all modalities and significantly lower than almost all the other digital systems ($P \leq 0.02$; except for Visualix). All observers tended to agree on the low sensitivity scores with the VistaRay system (Fig. 3). Further, Visualix images had lower sensitivity than CDR-APS, Dixi2, and Dr. Suni Plus images ($P \leq 0.003$).

On the other hand, the two RVGui image modalities showed the lowest mean specificity values. Due to the fact that some observers obtained very low sensitivities and thus made no false positive scores, their specificities were 100%. However, the variation among observers in specificity was also highest for the RVG systems (Fig. 3). It was not possible statistically to reveal differences in specificities among the systems due to the number of observers who obtained 100% specificity. For overall accuracy, the differences among the modalities were non-significant ($P > 0.05$).

**Table 3** The true status of the 160 approximal surfaces according to histological examination

| | No. of tooth surfaces | % |
|---|---|---|
| Sound surfaces | 103 | 64.4 |
| Enamel carious lesions | 48 | 30.0 |
| Dentine lesions extending ≤1/3 into dentine | 9 | 5.6 |
| Total | 160 | 100 |

## Discussion

Digital radiography has become widely accepted, and a number of studies using direct digital intraoral radiography have established that digital systems perform as accurately as conventional film for approximal caries detection [1, 9, 17, 20, 21, 25, 26]. In contrast to conventional film radiography, the image quality of digital images may be interactively post-processed by various enhancement procedures during and after image acquisition. Differences between un-enhanced digital images and enhanced images in a subjective evaluation of image quality was observed by Woolhiser et al. [28], with enhanced digital images receiving the highest rating. According to Wenzel et al. [24], filtering of a digital image may result in a reduction of blur of structure boundaries, but filtering also introduces noise in the image. A previous study evaluated observers' preferences of intraoral images treated with two high-pass filters (a monodimensional band-pass and a Laplacian-type filter) and a low-pass smoothening filter [26]. It was shown that while the high-pass filters were preferred for enhancement of bone structures, the low-pass filter was preferred in bitewings for caries diagnosis. Images treated with high-pass filters appear sharper, but also grainier than their originals while low-pass filtered images appear "softer". Therefore, the subtle boundary between sound and diseased

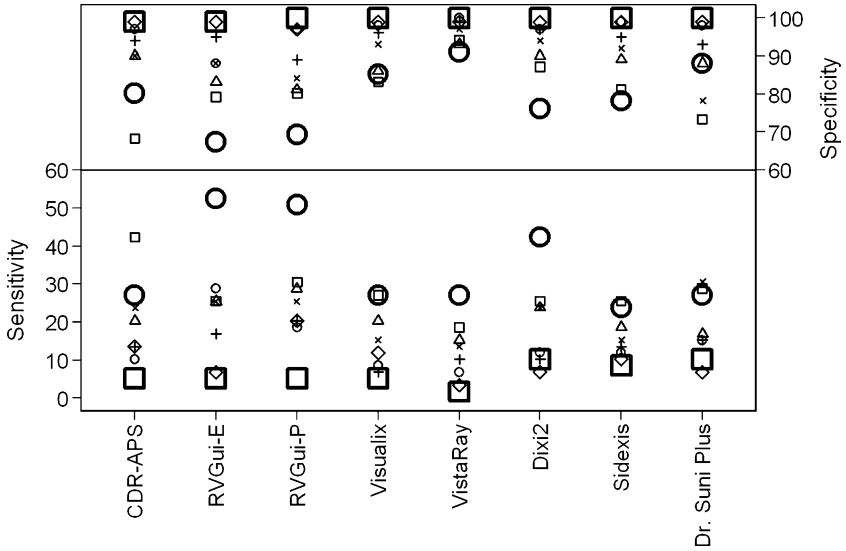


**Fig. 3** Sensitivities and specificities for eight observers with eight radiographic modalities (*large circle*: an observer obtaining high sensitivities and low specificities with the Kodak RVG modalities; *large square*: an observer obtaining very low sensitivities and very high specificities with all modalities). The other observers scored more homogeneously

tissues in small caries lesions may not be easier to be detected with high-pass filtered images.

The present in vitro investigation was conducted to compare images from solid-state digital receptors with particular emphasis on the task-dependent filters available for the Kodak RVGui system. It has not been possible to obtain detailed information on the nature of these filters; visually the images appear sharper, but also more coarse-grained than non-enhanced images. It seems, therefore, from the appearance of the images that they are treated with high-pass filters. The manufacturer of the RVGui digital system advocates that, at the time of image acquisition, the "dento-enamel" mode should be used for diagnosis of caries lesions, while the "periodontal" mode should be used for assessment of the marginal bone level. It is noteworthy from the results of the present study, that the "periodontal" and "dento-enamel" mode images showed comparable performances for the same diagnostic task, approximal caries detection. A previous study found accordingly that the "periodontal" mode images performed as well as "dento-enamel" mode images for approximal caries diagnosis [1]. The findings of these studies seem to indicate that an image acquired with the "periodontal" mode may be just as efficient (high sensitivity) for caries detection as an image acquired with the "dento-enamel" mode, i.e., it may not be justified to define these modes as "task-specific" algorithms. On the other hand, no study has yet evaluated these modes for assessment of the marginal bone level.

Previous studies have found that image enhancement significantly improved the detection of approximal caries [14–16, 18, 23, 27], caries lesion depth estimation, and observer agreement [19]. However, in other studies enhanced digital images had the same or lower diagnostic accuracy for caries detection than un-enhanced digital images and conventional radiographs [5, 8, 12, 13, 21]. In our study, post-processing by use of contrast, brightness, gamma curve function, and zoom was allowed. While almost all images, no matter which modality, were enhanced in some way by the observers, approximately one third of the images had undergone zooming. A recent study found that zooming using the bicubic convolution method had no influence on observer performance and diagnostic accuracy [3]. A possible influence of zooming was not tested in our study, but zooming was hardly likely to affect the results since this function was used in almost the same fraction of the images from each modality and not only, as might have been

**Table 4** Mean percentage (and range) for sensitivity, specificity, and overall accuracy for each radiographic modality: CDR-APS, RVGui "enamel", RVGui "periodontal", Visualix, VistaRay, Dixi2, Sidexis, and Dr. Suni Plus

| | CDR-APS | RVGui-E | RVGui-P | Visualix | VistaRay | Dixi2 | Sidexis | Dr. Suni Plus |
|---|---|---|---|---|---|---|---|---|
| Sensitivity | 19 (5–42) | 23 (5–53) | 25 (5–51) | 15 (5–27) | 12 (2–27) | 19 (10–42) | 16 (8–25) | 19 (7–31) |
| Specificity | 90 (68–99) | 87 (67–99) | 87 (69–100) | 93 (83–100) | 97 (91–100) | 93 (76–100) | 92 (78–100) | 90 (73–100) |
| Overall accuracy | 64 (59–68) | 64 (59–66) | 64 (62–69) | 64 (62–67) | 65 (64–68) | 66 (64–68) | 64 (58–67) | 64 (57–68) |

expected, in the high-resolution images (to make the image appear smaller to fit the monitor) or in the low-resolution images (to make the image look larger on the monitor).

The sensitivity of both RVG modalities in our study was significantly higher than for most of the other modalities. While a number of the observers indeed obtained their highest sensitivities with the RVG modalities, the highly significant differences between the RVG and the remaining modalities may be attributed mainly to one observer who detected particularly many lesions with this system. Conversely, the RVG images displayed the lowest specificity values mainly because of this same observer, even though this could not be statistically revealed due to the very high specificities for many other observers with most of the systems. We did not report the positive and negative predictive values in this study. Both these values and to a smaller extent the sensitivity and specificity are dependent on the disease frequency in the tooth sample. In our sample, the disease frequency was approximately 1/3, which may reflect the situation in many populations. In contrast to a previous study, which found a lower ROC curve area for approximal caries detection with RVGui images than with Dixi images and film [10], the overall accuracy was not significantly different between the systems in our study. In our study, we used a newly developed statistical method which is able to test discrete data. We find this method useful for caries accuracy data where it seems meaningful to obtain knowledge of true and false positive detection rates and, therefore, to test sensitivity and specificity separately instead of performing ROC analysis.

In conclusion, the overall accuracy differed little between solid-state digital receptor systems for detection of approximal carious lesions in non-cavitated surfaces, and no effect on accuracy could be demonstrated of task-specific filters with the Kodak RVG system. The highest observer variation was seen, however, for the RVG modalities, and the higher sensitivities obtained with the RVG modalities seemed to be due to one particular observer.

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