Original

Analysis of Signal Fading of Photostimulable Phosphor Plate System and Its Effect on the Accuracy in Detecting Proximal Caries

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Abstract: To clarify 1) how the signal fading effect occurs and 2) the diagnostic quality of the signal fading image in caries diagnosis. The Digora Optime (Soredex, Helsinki, Finland) system was used. Aluminum step wedges of 1 to 10 mm thickness and 1-mm-thick lead were used. Exposed photo-stimulated phosphor imaging plates (PSP-IPs) were scanned at six different intervals: immediately, 3, 6, 24, 72, and 144 h. Two kinds of scanning modes were used: with and without auto enhancement correction (AEC). The gray value difference between the immediate and delayed scanning images in the same objective area was calculated as the signal fading effect value (FEV). Thirty extracted upper premolar teeth (carious: 42 surfaces) were used. Immediate, 3, 24, and 72 h delayed scan images were created. Four observers assessed them. The Friedman test was used for statistical analysis and statistical significance was $p<0.05$. Analysis of the without AEC image revealed that the signal fading had the same gray value change. This change was not related to the initial gray value. In the processing of AEC, the middle part of the gray value tended to be more enhanced. Significant differences in gray value changes were observed after 3 h, but no statistically significant difference was seen in the caries diagnosis. The area under the receiver operating characteristic (ROC) curve (Az) from immediate, 3, 24, and 72 h delayed images was 0. 61±0. 17, 0. 56±0. 04, 0. 67±0. 04, and 0. 58±0. 06.

Key words: signal fading, photo-stimulated phosphor plate system, diagnosis of interproximal caries.

A number of digital radiography systems have been widely used in general dental offices over the last decade. Figure 1 shows the imaging processing flow diagram of the photo-stimulated phosphor imaging plate (PSP-IP) system. In this system, the ionizing radiation is absorbed in the phosphor and stored within the phosphor crystal lattice, forming a metastable combination that has a finite time before the spontaneous recombination of the trapped electrons and Eu^{3+}, which is referred to as "signal fading".

Signal fading can be described as the natural loss of the stored energy from within a phosphor crystal lattice. The potential loss of a stored digital signal in a phosphor crystal is known to be thermal and time sensitive. Thus, signal fading of the trapped signal in the storage phosphor imaging plate occurs exponentially over time as a result of spontaneous phosphorescence (Eu^{3+} plus e-fades to Eu^{2+}). Sample fading images, includes immediate, scanning delayed with 3, 24 and 72 h, were shown in Fig. 2. When scanning was more delayed, the image was deteriorated.

More than 25% of the stored energy can be lost with the first 10 min to 8 h from the time of exposure.[1, 2] Borg and Gröndahl[3] reported that only 50% of the X-ray energy that comes in contact with the imaging plate is used to produce a latent image. The peak energy level stored in the proper crystal is highest after the imaging plate is initially exposed to ionizing radiation. Couture and Hildebolt[4] tested signal fading effects on images of step-wedge with storage phosphor imaging plates scanned with a delay ranging from 6 to 37 min. They found no change in dose ratios between different steps in the step-wedge images. They reported that signal loss after exposure affected the pixel intensity of

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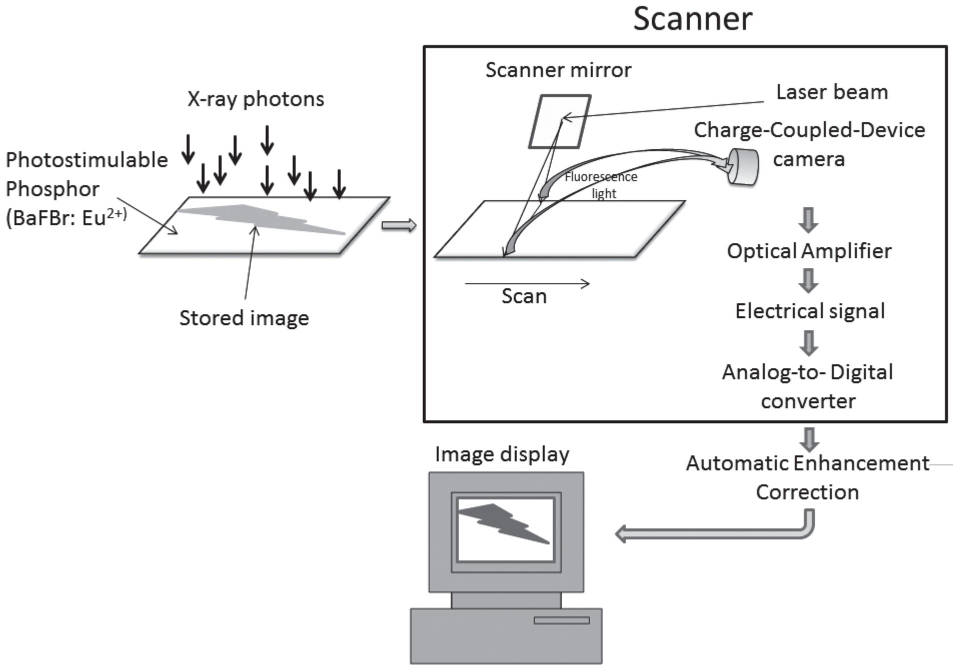

Fig. 1 The PSP-IP imaging processing flow diagram. When X-rays are exposed to the imaging plate, the trapping elements that are produced by crystals are able to store a significant amount of the X-ray energy, creating a latent radiographic image. A stimulating helium neon laser beam is then used to pump the electrons into a state in which energy transfer will take place that produces a stimulated visible light that can be corrected and digitized.

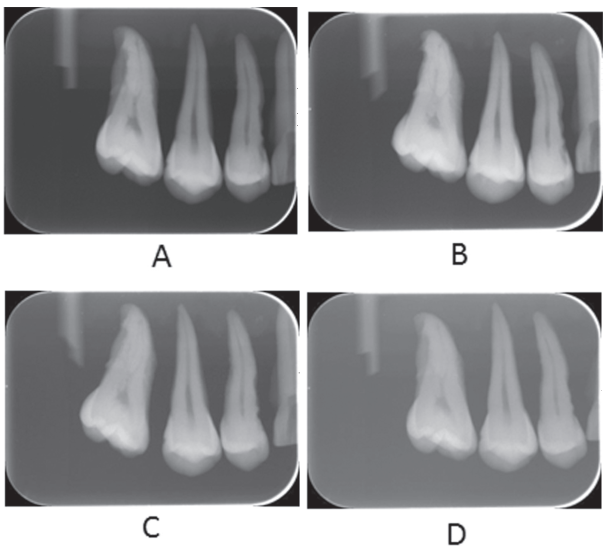

Fig. 2 Sample fading image. Immediate scanning image (A), scanning delayed with 3 h (B), 24 h (C), and 72 h (D) were shown. When scanning was delayed, the image was deteriorated.

the corresponding digital image of each step equally, regardless of the thickness. Couture[5] analyzed one of the PSP-IP system, named the DenOptix system. He concluded that signal loss due to delay affected the resulting image in a similar manner to how radiation is affected by exposure dose. According to his calculations, a delay of 30 min in scanning was equivalent to a 22% decrease in exposure.

Okamura et al.[6] analyzed another PSP-IP system, named Digora Optime system. The gray level of this system is almost logarithmically decreased with exposure, which was similar to the characteristic curve of typical intraoral film systems with the “Automatic enhancement correction” (AEC) mode. This AEC program was already installed in this system and the scanned data was automatically translated into the suitable image to observe using this program and the results were displayed in the monitor. Such manipulation could affect the gray level in the images obtained in the delayed scan in such whether the gray level is decreased proportionally or not depending on the initial gray level.

Figure 3 shows the sample of Digora Optime images with the aluminum step wedge consisting of steps the1, 1.5, 2, 3, 4, 6, 8 and 10 mm thick and subtracted image were shown. The immediate scanning image (A) and

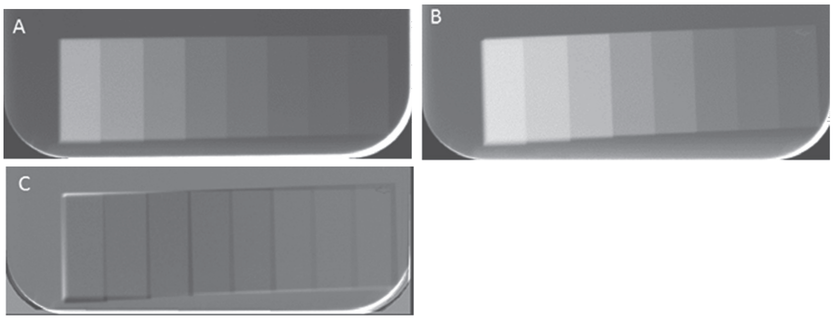

Fig. 3 The immediate scanning image (A), 72 h delayed scanning images (B) and the images obtained by subtracting these two images (C). These images are shows 1 to 10 mm thickness of the aluminum step wedge. Focus to the subtraction image, the step images from the third through 5th aluminum step wedge from the left, was darker than that of others.

the 72 h scanning delayed image (B) and the subtracted image (C) that subtracted the immediate scanning image (A) and the 72 h scanning delayed image (B) without any density adjustment, were shown. In this image, the gray color areas of 2 to 4 mm thickness of the step wedge were darker than other areas. These subtracted images suggest that signal fading did occur unevenly. If the ratio of signal fading was different on the PSP-IP, it may be difficult to diagnose caries, because, for caries diagnosis, the most important thing is "the presence of different gray areas in the area of focus." Our research focuses on this issue.

In this study, we seek to determine how signal fading occurs in the AEC image which includes the light parts and the dark parts of each PSP-IP. We examine if the signal loss after exposure is affected by the pixel intensity of the corresponding AEC image of each step equally, regardless of the thickness of the step. The purposes of our study are to clarify how signal fading occurs on the AEC image and to assess how signal fading affects caries diagnosis.

Materials and Methods

1. Basic research of signal fading

1) Create measurement of image

The Digora Optime (Soredex, Helsinki, Finland) system and five imaging plates were used in this study. This system was developed for intraoral radiographic examination. An aluminum step-wedge in thickness of 1, 1.5, 2, 3, 4, 6, 8, and 10 mm coupled with 1 mm thickness of lead was used as a test object. An intraoral X-ray unit (HD-70, Asahi Roentgen, Kyoto, Japan) with a round collimation focal spot size of 0.8 mm, total filtration of 25 mm Al equivalence and 60 kV, 7 mA, and 0.08 s operation was used for all PSP plates. This X-ray unit was also developed for intraoral radiographic examination. A 20 cm focus-to-sensor distance was used in this study. The exposure setting was confirmed to produce optimum image quality by consensus agreement between two oral radiologists by evaluating a sequence of images with exposure time ranging from 0.04 to 0.12 s. All exposed PSP plates were scanned before and after the AEC. The scanning pixel size was set at 40 μm.

The first set of five exposed PSP plates was scanned immediately, first scan was used without AEC and then retrieve AEC. After, the same PSP plates were exposed once more and immediately placed into a storage box (part of the Digora Optime system) until scanning time (3, 6, 24, 72, and 144 h delay), and then placed in a dark room. In this manner, 60 images were captured: five without AEC images and five AEC images for one immediate and five kinds of scanning delay time images for each scanning time.

2) Measurement of the signal fading effect

In each image, 10 areas of gray values were measured (i. e. , the background, the eight steps of the aluminum step wedge, and the 1-mm-thick lead), using Image J software (ver. 1.4, NIH, Bethesda, MD, USA). The region of interest (ROI) was set at 50×50 pixels. The signal fading effect was evaluated as a value obtained by subtracting the gray levels of the same step in the immediate and delayed images. Fading effect value (FEV) was calculated as the difference of gray value between immediate and scanning delayed images in each step (measurement area) and each scanning delay. The FEV was compared for each without AEC image and AEC image for each scanning delay. Using the data from each step, it was possible to compare the size of signal fading in each measurement areas of the same image.

3) Statistical analysis

In order to assess if the pixel value changed as a result of the thickness of the step, the FEVs in each measurement area were compared in the same image. SPSS statistical analysis software (Ver. 14) (SPSS Inc., Chicago, IL) was used to determine the signal fading of both light and dark areas on the same image, to see if the same change in gray value occurred on the before AEC image and the AEC image, and to assess the gray value difference due to scanning times delay. Repeated measures analysis of variance (ANOVA) ($p<0.05$) was used and the Bonferroni/Dunn multiple comparison test was used to assess the difference between each measurement.

2. Signal fading effects for caries diagnosis

1) Create a signal fading interproximal caries image

The signal fading effect for caries diagnosis was examined in the following methods. Thirty extracted human upper premolars with both sound and incipient caries on the proximal surfaces were used in this study. Forty-two surfaces had caries present (enamel: 29 surfaces; penetrated into dentin: 13 surfaces), which was confirmed by a micro computed tomography (XCT Research SA+: Stratec Medizinlehnik, GMBH, Germany). The teeth were fixed by plastic block and utility wax (GC Dental; Tokyo, Japan). Each block consisted of two premolars and one molar and one canine were used to secure proximal contact for each premolar. The tooth blocks were positioned in a jig to provide a central beam orientation, and the PSP plate was placed behind the block in close contact. The presence of soft tissue was simulated by placing a 1-cm-thick piece of a soft-tissue equivalent material (Tough Water Phantom, Kyotokagaku, Kyoto, Japan) in the appropriate place.

All teeth were radiographed separately under standard conditions using the same X-ray unit (HD-70, Asahi roentgen, Kyoto, Japan). Exposure was set at 60 kV, 7 mA, and 0.12 s. The focus-to-sensor distance was set at 26 cm. In this caries study same as the clinical conditions, the AEC image was assessed. The first set of images (30 teeth) was scanned immediately after exposure. The remaining three (3, 24, and 72 h) sets of PSP plates were stored in a storage box and scanned at the delayed time. A total of 60 images (consisting of 15 immediate images and three sets of different scanned images) were obtained and 120 surfaces were diagnosed.

2) Imaging interpretation

One general dentist and three oral radiologists, with the experience between 20 and 30 years, assessed the images. The observers were also required to have a good knowledge of the effects of image manipulations. Observers were shown these images randomly and when they observed image, they were allowed to adjust the contrast and brightness of images. No time limit was set for viewing the sequence of images. Before the viewing session, observers were trained with a sample image. The rating session took place in a dimmed reading room using the Digora for Windows software (Ver. 2.7) with a 13-inch VGA computer monitor operating at 1024×768 pixels. During the viewing session, the observers were asked to rate the possibility of the presence of interproximal caries using a five-point scale. They were also asked to use a two-point scale to rate the presence or absence of caries.

3) Assessment of caries diagnosis and statistical analysis

The diagnostic accuracy was assessed as the area beneath the receiver operating characteristic (ROC) curve (Az). ROC curves were made each scanning delay, using SPSS statistical analysis software (ver. 14, SPSS Inc, Chicago, IL). The two-point scale data was used to

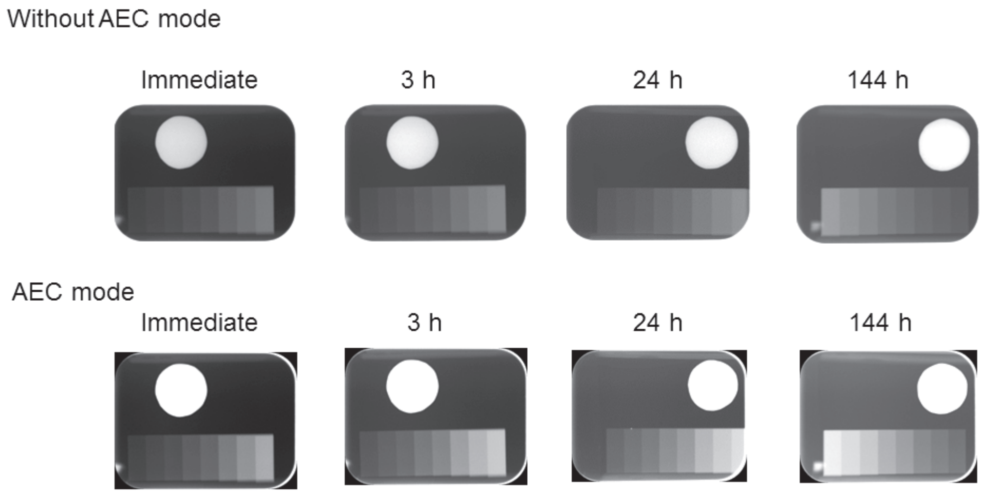

Fig. 4 Sample images of immediate, 3, 24, 72, and 144 h delayed scanned images in without auto enhancement correction (AEC) and AEC. In the AEC, the gray value of the 1 mm thickness of lead was translated to 255, which is the maximum of the 8-bit gray level. This trend was observed in all AEC images, regardless of the scanning delay.

measure the sensitivity, specificity, and accuracy.

These data were estimated by analyzing the addictive effects of the scanning delay. Statistical analyses were determined by Friedman test. The level of statistical significance was $p<0.05$. These data were analyzed by SPSS statistical analysis software (ver. 14, SPSS Inc, Chicago, IL).

Results

1. Basic research on signal fading

The images with the signal fading of the without AEC and the AEC in the immediate, 3, 6, 24, 72, and 144 h delayed images are shown in Fig. 4. In the AEC, the gray value of the 1 mm thickness of lead was translated to 255, which was the maximum number of the 8-bit gray level. This trend was observed in all AEC images, regardless of the scanning delay.

The changes in gray values from dark to light areas were shown in Fig. 5 with regard to the without AEC and the AEC images by immediate scanning.

Comparison of gray values in the AEC and the without AEC image, the difference of gray values getting larger revealed with the wedge thickness. Each measurement area, the difference in gray value was not uniform on the image with AEC. Higher gray value area such as thicker wedge, was changed into more higher gray value in the AEC image.

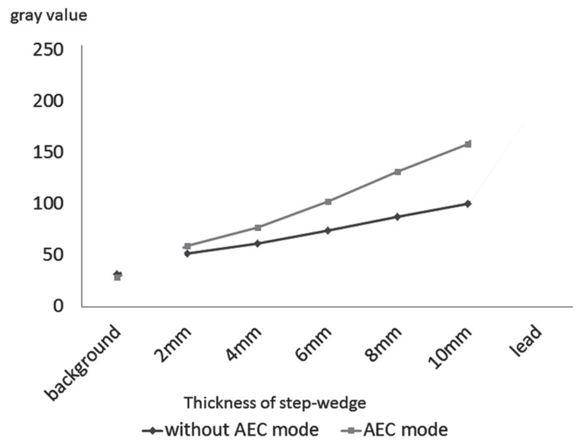

Fig. 5 The gray values in background, 2, 4, 6, 8, 10 mm thickness of aluminum step-wedge and lead area in the without AEC image and the AEC image, which were obtained immediately scanning. In the AEC images, the gray value was changed; this was related to the initial gray value. In comparison with the each measurement, the gray value of the AEC were getting higher, it depend on the gray value of the thickness of the wedge.

Figure 6 shows the FEVs of all steps of the wedge subtracted from the immediately scanned plates and those scanned after delays ranging from 3 to 144 h in the without AEC image (A) and the AEC image (B). The FEVs increased with the increase in scanning delay. Each line represents a change in the gray value of the signal fading image made with a different time lapse. The range

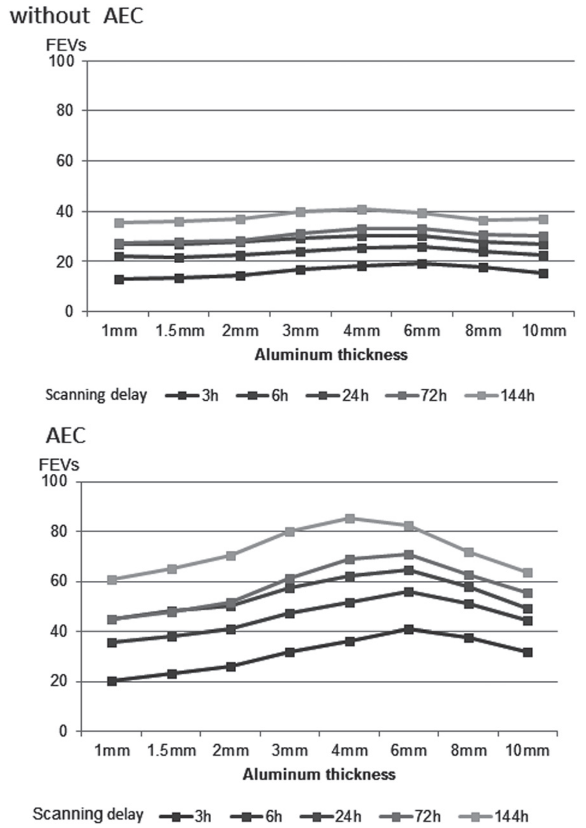

Fig. 6 Signal fading effect value (FEV) of each measurement area in the without AEC and the AEC in a latent image in the aluminum step wedge area. Each line represents a change in gray value of the signal fading image made with a different time lapse. Focus on the FEVs of the aluminum step wedge area, the without AEC, was almost flat. This suggests that fading occurred equally, regardless of the initial gray value. Comparing the FEVs of 3 and 144 h, the AEC image increased more than the without AEC image. In the AEC image, the peak of the FEVs was changed from 6 mm to 4 mm with increasing scanning delay.

of the standard deviation (SD) in the before AEC image was 1.40 to 2.23 and that of the AEC image was 7.18 to 9.53. In the AEC mode, the graph shows that the peak of the FEVs changed from 6 to 4 mm with increasing scanning delay.

The signal loss after exposure affected the gray value of the without AEC image of each step equally, regardless of the thickness of the step. The range of FEVs of the AEC mode was wider than those of the without AEC mode.

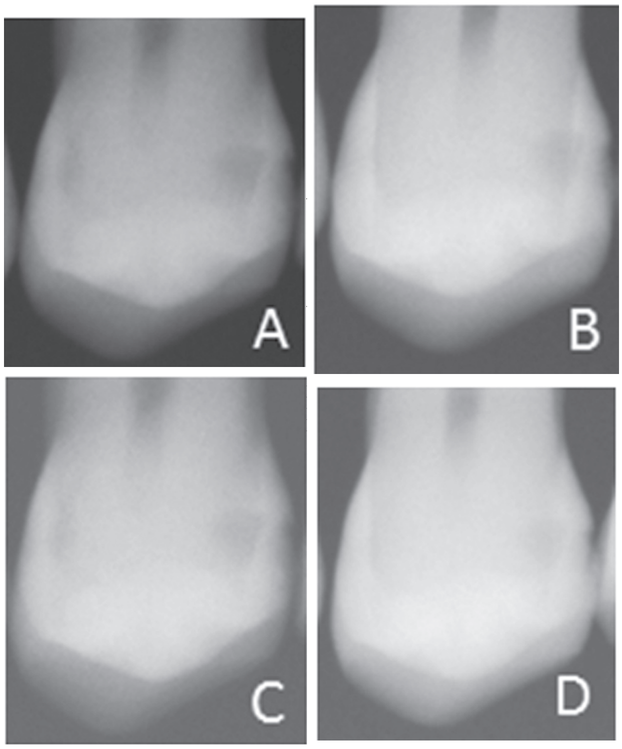

Fig. 7 Sample radiographic images showing immediate (A), 3 h (B), 24 h (C), and 72 h (D) scanning delay. These images had no adjustment of contrast or brightness. The left side of the radiolucent area in the 24 h image (C) is more clear than that of other images.

In comparison with each wedge thickness on the AEC, the FEVs of 3 to 6 mm thickness were larger than other thinner and thicker wedge area. Also until the 72 h delayed image, the maximum FEV was observed at the 6 mm thickness and in the 144 h delayed image, the peak of FEV was shifted from 6 mm to 4 mm thickness.

In the FEVs of scanning delay in the without AEC mode, a statistically significant difference was seen for all scanning delay times. The p-value of 3 h was 0.017, and that of 6 h was 0.002. For scanning delay times of more than 24 h, the level of significance increased and the p-value was less than 0.0001. In the AEC mode, significant differences were observed for all scanning delay times. The p-values for all scanning delay times were less than 0.0001.

In the AEC mode, statistically significant difference levels were higher than those for the without AEC mode. Also, the significant difference in the FEVs of the

Table 1 The mean±standard deviation (SD) of the sensitivity, specificity, accuracy, and the ROC area (Az) for each time delayed image. There is no significant difference between the observers and the time delay in the detection of proximal caries.

	Scanning Delay			
	0 h	3 h	24 h	72 h
Sensitivity	0.52±0.22	0.46±0.16	0.52±0.13	0.44±0.21
Specificity	0.69±0.21	0.78±0.26	0.76±0.12	0.74±0.27
Accuracy	0.57±0.10	0.56±0.09	0.59±0.06	0.54±0.09
Az	0.61±0.17	0.56±0.04	0.67±0.04	0.58±0.06

background and the 1-mm-thick lead were significantly different for all scan delays ($p<0.0001$).

2. Signal fading effect for caries diagnosis

Figure 7 shows images of premolar teeth that have radiolucent areas in the mesial and distal interproximal area. These images did not adjust the contrast or brightness. In the 72 h delayed image, the right side of the radiolucent area remains visible. The left side of the radiolucent area became unclear. This decay is still visible in the 24 h delayed image. Table 1 shows the mean and SD of the sensitivity, specificity, accuracy, and Az. There is no statistically significant difference in the all of diagnoses using the immediate, the 3 h, the 24 h and the 72 h delayed images. There is no trend between diagnostic accuracy and scanning delay.

Discussion

Several studies related to signal fading have been published.[1,5,7~14] They concluded that the mean gray value increased with scan delay. However, there is no study about the ratio of fading was affected to the degree of the stored X-ray energy on the PSP-IP. In our study, statistically significant difference was seen in all measurement areas in each mode and each scanning delay. Also, we suggested that the FEVs in the without AEC image were almost the same in each step wedge in comparison with the FEVs in the without AEC image. However, in comparison to the gray value of the AEC image in each scanning delay, the slope became steeper and the high gray value area was also enhanced. Comparison of the gray values revealed that they increased with increases in the AEC mode. This result suggests that in sometimes, the gray value area where caries are present may be more enhanced in fading image; this change may be related to more frequent misreading but in some case, this change could make it easier to detect caries.

The visibilities of the human anatomical structure in signal fading images, were assessed by Ang et al.[14] They used the different kind of PSP system, named DenOptix system. The subject was used the cadaver of upper canine with a reamer, which was mas made for simulate root canal treatment. Observers assessed a maximum of 168 h delayed image. They suggested that there is no difference in the visibility of images. The gray value was statistically significantly changed by the signal fading effect, but this signal fading image did not affect the image quality until a 4 h scanning delay. This suggests that signal fading occurs but that it may not affect the clinical diagnosis.

In clinically, we usually use the AEC effect in the Digora Optime system. In this caries study, we did the same conditions. In this study, there was no statistically significant difference in caries diagnosis. It suggests that the gray value change as a result of signal fading did not affect the caries diagnosis. In some cases, the detectability of caries of signal fading images decreased with greater scanning delay, but in some cases, the detectability was higher than that of immediate images. The concern with signal fading images is that they tended to be enhanced to different gray values, and it may have become easier to detect the presence of caries in some of the signal fading images. It is difficult to determine how to adjust the image for detecting caries. There are many factors and variations in tooth structure, including enamel thickness, the ratio of minerals missing, and cavity depth. As such, it remains a challenge to create filters that would enable the detection of the presence of caries. In some digital system have an caries diagnostic assist program. The effectiveness of an image enhancement program that was made for caries diagnosis was assessed by Haiter-Neto et al.[15] They used different PSP-IP system, VistaScan. This program has task-specific filters, “caries 1” and “caries 2.” They assessed the accuracy of caries diagnosis using these filters. They concluded that these caries filters were less accurate than the original images and were therefore not recommended for the detection of caries.

By analyzing the results that were obtained from the measurement of the gray values of the without AEC images and the AEC images, different gray value areas may be more enhanced by signal fading images with AEC. Signal fading images with the AEC may sometimes be helpful in caries diagnosis.

Okamura et al.[6] concluded that Digora Optime images almost logarithmically decreased with exposure, similar to the characteristic curve of typical intraoral film systems. However, the manufacturer does not provide instructions on how to convert the scanned gray value by AEC.

Almost all of the signal fading effect research utilized AEC images. In this study, we analyzed the with and without AEC image. As Okamura et al.[6] suggested that the Digora Optime system cannot avoid the AEC effect completely. In this study, we also could not avoid the AFC effect completely. As such, this was a limitation to analyzing how signal fading occurs on PSP-IPs.

Conclusions

In this study, we concluded that on the without AEC signal fading occurred at the same gray value change and that this change was not related to the initial gray value. However, in the signal fading image with the AEC, the different gray value areas were enhanced and this change sometimes made it either easier or more difficult to detect the presence of caries. In the future study, we will plan to compare the detectability of bony change in the fading image with and without AEC.

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