Polarized Versus Nonpolarized Digital Images for the Measurement of Demineralization Surrounding Orthodontic Brackets

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ABSTRACT
Objective: To compare the assessment of demineralized white lesions surrounding orthodontic brackets using images produced with and without polarizing filters to reduce incidental flash reflection.

Materials and Methods: Thirty teeth with orthodontic brackets and a systematic arrangement of artificially induced demineralization were used. Standardized digital images of the teeth were taken with and without a cross-polarizing filter. These were repeated after 1 week. All the images were randomly numbered and assessed by an investigator, unaware as to the nature of the study. The presence or absence of demineralization was recorded and compared with the actual demineralization pattern. The lesion area and degree of whiteness (LI%) were measured using computerized image analysis. Twenty images from each group were randomly chosen and duplicated for an assessment of measurement error.

Results: The positive and negative predictive values were better from the polarized images (0.97 and 0.84, respectively) than from the nonpolarized images (0.90 and 0.74, respectively). The percentage agreements for the repeat assessments of the same slide were better for the polarized images (96%) than for the nonpolarized images (89%). The limits of agreement and intraclass correlation coefficients between measurements of repeated images were lower for lesion area from cross-polarized images, suggesting better reproducibility, but not for LI%.

Conclusion: A cross-polarization filter enhances the subjective assessment of demineralized lesions surrounding an orthodontic bracket and improves the reproducibility of measuring the lesion area. The filter did not improve the assessment of changes in enamel gray levels with demineralization.

KEY WORDS: Orthodontics; Dental caries; Image analysis; Demineralization; Cross-polarization

INTRODUCTION
Clinical photographs are frequently used to record the appearance of teeth before and after orthodontic treatment to assess the presence of white spot demineralization. One disadvantage of flash photography is that it will tend to overestimate the prevalence of white opacities on the teeth. This is mainly due to the appearance of reflections from the flash that might mimic the appearance of white spot demineralization. One method of reducing the reflections is to take the photographs at an angle to ensure that the flash is not reflected back into the lens. The disadvantage of this technique is the potential variability in the angle at which the camera is held, which may lead to differences between different operators or within one operator over time. An alternative method to reduce unwanted reflections is the use of polarizing filters.

Light is part of the electromagnetic spectrum. It is an electromagnetic wave consisting of a traveling pattern of an electric field in one plane and a magnetic field in another plane; however, these planes are not all orientated in the same direction. A polarizing material consists of a sheet of stretched and partially...
aligned strands of polyvinyl alcohol and iodine atoms lying along each molecular chain. These molecules absorb the electric fields traveling parallel to them. Electric fields traveling at right angles to the molecules are not absorbed. Therefore, light emerging from the polarizing material is called plane polarized because it consists of an electric field traveling along the polarizing transmission axis.7

Unwanted light from a camera flash can be reduced using a technique called cross-polarization.8 Light emitted from the flash can be plane polarized by placing a polarizing filter over the flash unit. This light, with the electric field traveling in one plane, can be prevented from entering the camera by placing a second polarizing filter over the lens. This second filter is aligned such that the polarizing molecules are at right angles to the first filter, hence absorbing the plane-polarized light from the flash.

Cross-polarization has been used in clinical trials to reduce reflections from the flash and improve the assessment of acne9 as well as enamel opacities.8

The aim of this study was to evaluate the use of cross-polarized images in the assessment and measurement of artificially induced demineralized lesions surrounding orthodontic brackets. The hypothesis was that the use of cross-polarization filters would lead to an improvement in the subjective assessment of demineralization from digital images and in the reproducibility of measuring lesion size and opacity using computerized image analysis.

MATERIALS AND METHODS

The material used in this in vitro study has been described previously,10 but to summarize briefly, 15 extracted human molars were used because it was not possible to obtain a large enough sample of human incisor teeth. They were carefully inspected to ensure the clinical absence of white spot lesions. The teeth were divided in half and shaped to resemble incisors. A unique identifying number was engraved on the cut surface of each half tooth.

Standard edgewise 0.018- x 0.025-inch twin brackets (Ortho-Care [UK] Ltd, Bradford, West Yorks, UK) were bonded to the surface in the usual position for an orthodontic attachment. The crowns of the teeth were covered with three coats of acid-resistant varnish except for windows approximately 1.5 x 3 mm of enamel surface on the gingival, occlusal, left, and right aspects of the bracket. The teeth were placed in an acidified gel system consisting of 0.1 M lactic acid and 0.1 M sodium hydroxide, mixed in proportions to give a pH of 4.5, and 6% (w/v) hydroxyethylcellulose was added to produce the gel consistency. The tooth surface with the bracket was incrementally coated with acid-resistant varnish in a systematic arrangement to expose the four windows to the dematerializing gel for 0, 3, 7, or 14 days. The presence of demineralization was confirmed and measured using quantitative light-induced fluorescence.11

Production of the Images

Standardized images of the teeth were taken using a FinePix S1 Pro camera (FUJIFILM Electronic Imaging Ltd, Hemel Hempstead, UK) with a 105 mm/2.8 AF Micro Nikkor lens. The image size was set at 1440 x 960 pixels, image quality fine, and ISO sensitivity 400. Images were captured on a 32-MB CompactFlash card (Lexar Media Inc, Fremont, Calif) as JPG images.

A Cokin flash (Cokin SA: Silic 457-94593, Rungis Cedex, France) was used (Figure 1). For the polarized images, strips of linear polarizing acetate (Jessops, Leicester, UK) were placed over the tubes to polarize the light in the vertical plane and standard linear polarizing filter with orientation markers placed over the lens to polarize light in the horizontal plane.

Figure 1. FinePix S1 Pro camera and Cokin flash. The arrows indicate the linear polarizing acetate with orientation markers placed over the flash tubes to polarize the light in the vertical plane and standard linear polarizing filter with orientation markers placed over the lens to polarize light in the horizontal plane.
Figure 2. Images of a tooth taken (a) without and (b) with polarizing filters. A demineralized white area can be seen to the left of the bracket, and the white area of flash reflection underneath the bracket in (a) is removed with the filters in (b).

The images of each tooth were repeated after 1 week, during which the teeth were stored in water. Twenty nonpolarized images (NPI) and polarized images (PIs) were randomly chosen and duplicated to determine the reproducibility of the within-investigator method. All the images were numbered and recoded in a random order, placed on a CD-ROM, and given to a second investigator (A.A.S.) who had not been involved in the production of the images and was not informed about the nature of the investigation.

Analysis of the Images

The second investigator carried out two assessments. First, the investigator determined for each side of the bracket (gingival, occlusal, right, and left) whether he believed demineralization was present. Second, the investigator used computerized image analysis (Image Pro Plus, version 4.0; Media Cybernetics; Bethesda, MD, USA) to measure the area and mean 8-bit gray level (256 gray levels) of any lesions detected. Calibration of the images was performed using the known width of the orthodontic bracket tie wings. A second measurement to assess whiteness for luminosity was taken from an area deemed to be sound enamel, and the luminance intensity proportionality was calculated using the following formula:

$$LI\% = \left( \frac{\text{Mean gray level of white lesion}}{\text{Mean gray level of sound enamel}} - 1 \right) \times 100$$

Statistics

The following analyses were carried out to assess the validity and the reproducibility of the assessments from the PIs and NPIs:

1. To measure validity, the subjective assessments regarding the presence or absence of demineralization by the judge were used. This was compared with the actual demineralization pattern carried out on each tooth. The sensitivity, specificity, positive predictive value, and negative predictive value were calculated for the 240 assessments made with the two techniques (30 teeth, two images of each tooth, four sides to each bracket).

2. The percentage agreement between the subjective assessments of the two images taken of the same tooth 1 week apart was calculated using the following formula:

$$\frac{\text{Total number of assessments} - \text{change between first and second image}}{\text{Total number of assessments}} \times 100$$

3. The agreement between the objective assessments (demineralized lesion area and luminance intensity proportionality [LI%]) of the two images taken of the same tooth 1 week apart was assessed using the limits of agreement and a paired t-test for systematic error. Values from sites were used only when there was a reading from both the NPIs and PIs.

In addition, the within-investigator agreement was assessed using the 20 duplicates of the same image. The intraclass correlation coefficients were calculated for the demineralized lesion area and LI% from the sites where there was agreement that demineralization was present on the first and second duplicate images. The levels of agreement were based on those described by Landis and Koch.

RESULTS

The sensitivity, specificity, positive predictive value, and negative predictive values for the NPIs and PIs are shown in Table 1. The results for the PIs were
Table 1. Sensitivity, Specificity, Positive Predictive Values (PPVs), and Negative Predictive Values (NPVs) for the Nonpolarized Images (NPIs) and the Polarized Images (PIs) Calculated From the Subjective Assessment for the Presence/Absence of Demineralization of All the Demineralized Areas (14, 7, and 3 days; n = 240 assessments) and for Just the 14- and 7-Day Demineralization (n = 200 assessments)

<table>
<thead>
<tr>
<th>14-, 7-, and 3-Day Demineralization</th>
<th>14- and 7-Day Demineralization</th>
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<tbody>
<tr>
<td>NPI</td>
<td>PI</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>0.47</td>
</tr>
<tr>
<td>Specificity</td>
<td>0.97</td>
</tr>
<tr>
<td>PPV</td>
<td>0.90</td>
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<tr>
<td>NPV</td>
<td>0.74</td>
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Table 3. The Intraclass Correlation Coefficients for Demineralized Lesion Area (mm²) and Luminance Intensity Percentage (LI%) From the Duplicated Nonpolarized Images (NPIs) and Polarized Images (PIs; n = 17 NPI sites and 25 PI sites)

<table>
<thead>
<tr>
<th></th>
<th>NPI</th>
<th>PI</th>
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<tbody>
<tr>
<td>Area</td>
<td>0.920</td>
<td>0.950</td>
</tr>
<tr>
<td>LI%</td>
<td>0.890</td>
<td>0.790</td>
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better than for the NPIs, as 71% of sites with demineralization were correctly identified from the PIs compared with only 47% from the NPIs. Most of the unidentified sites were those subjected to the demineralizing environment for 3 days. Table 1 shows that when these were removed, the sensitivity improved to 0.85 for the PIs and 0.65 for the NPIs. The specificity or the ability to correctly identify a site when it was not demineralized was good for both PIs (0.99) and NPIs (0.97).

Altman suggests that the positive and negative predictive values are more relevant values than the sensitivity and specificity, as they explore the probability that the diagnosis is correct. The positive predictive values were good for both NPIs (0.90) and PIs (0.97). To interpret this value, when the investigator decided that demineralization was present; it was indeed present for 90% of sites from NPIs and 97% of sites from PIs. The negative predictive values were lower for both NPIs (0.74) and PIs (0.84). Again, to interpret this, when the investigator decided that demineralization was not present, it was not present for 74% of sites from NPIs and 84% of sites from PIs. Both values improved significantly when the sites that were demineralized for only 3 days were excluded (0.89 and 0.95, respectively).

The agreement between the assessments on repeated images was very good for PIs. On only five occasions of the 120 repeated assessments (30 teeth, four sides to the bracket) did the investigator change his assessment as to the presence or absence of demineralization between the first and second image. This represents a 96% agreement between images. The reproducibility for NPIs was not so good. The investigator changed his assessment on 13 occasions, representing an 89% agreement between repeated images.

The mean differences and limits of agreement for the readings taken from the two images taken of the same tooth 1 week apart are shown in Table 2. The limits of agreement for the measurement of lesion area from the PIs were lower than for the NPIs, suggesting better agreement, but the mean difference was slightly greater for the PIs. A systematic error was detected ($P = .002$), which was not present with the NPIs ($P = .691$), but the mean difference was small (0.59 mm²) and unlikely to be clinically significant. The mean difference and limits of agreement for LI% were similar for both PIs and NPIs, with no systematic error detected.

The intraclass correlation coefficients for the repeated readings from the same images are shown in Table 3. The results showed excellent reliability except for the luminance intensity percentage, which showed moderate agreement for the PIs.

**DISCUSSION**

This study has found evidence that the use of the cross-polarization technique for reducing incidental reflections from the flash improves the subjective assessment of the presence or absence of demineralization surrounding an orthodontic bracket. There was also some evidence that the reproducibility of lesion area measurements was improved, but there was no evidence that cross-polarization of images improved
the objective assessment of changes in the enamel whiteness as represented by the gray scale.

The results of the subjective agreement in this study agree with those of Robertson and Toumba. They examined the use of cross-polarized photography in the assessment of enamel defects with the Developmental Defects of Enamel Epidemiology Index. They found that agreement between a group of investigators rose from 55% from the nonpolarized photographs to 90% from the cross-polarized photographs. This is greater than the rise from 89% to 96% in this study.

Lesion area and lesion LI are two measures of the severity of a demineralized lesion. The measurement of the lesion area from repeated images of the same tooth showed lower limits of agreement and a higher intraclass correlation coefficient when using cross-polarization, suggesting better agreement and a smaller random error. The measurement of LI showed a similar mean difference and limits of agreement but lower intraclass correlation coefficient from repeated images using cross-polarization, suggesting a higher random error.

The change in whiteness of demineralized enamel occurs due to an increase in the backscatter of light. When a light photon enters sound enamel, it travels an average distance of 0.1 mm before being scattered. Demineralized enamel is more porous than sound enamel, and the crystal structure is partly substituted with water. Light scattering in demineralized enamel is markedly higher due to the increased subsurface porosity, which leads to the whiter appearance of demineralized enamel. When the lesion is dried, the water is replaced by air, and the average refractive index declines even more, leading to an even whiter lesion. It is therefore important to standardize the dryness/wetness of the lesion before taking a photograph, and this was done by storing the teeth under wet conditions and drying them with a triple spray for 15 seconds before the image was taken.

There have been previous attempts to measure this backscatter using an optical caries monitor (OCM). A good correlation between the OCM data and chemical analysis of demineralized bovine enamel lesions was found; however, there was a poor correlation with transverse microradiography, which provides the gold standard for mineral loss in enamel and dentine. That might be due to a lack of homogeneity within a lesion, as variations in the lesion occur over distances smaller than 0.5 mm. This might also be a problem with the measurement of luminance intensity proportionality, which provides an average reading over the whole of the lesion. No attempt was made in this study to validate the technique with a gold standard of mineral loss.

More recently, a new technique, called polarization-sensitive optical coherence tomography, has been used to measure backscattered light as a function of optical depth in up to 3 mm of dental enamel on the occlusal surfaces of posterior teeth. Other nondestructive optical methods such as quantitative light-induced fluorescence have been used to quantify mineral loss in enamel. The disadvantage of these more sophisticated techniques is that they require the use of more expensive technology compared with digital photography, which most clinicians will employ routinely in their clinical practice.

One problem with any method of measurement is the variation in the quality of the images when monitoring lesions in patients over time. Potential sources of error include the positioning of the camera relative to the tooth and differences in shade of the image. We have tried to address the first problem by using the jig in the bracket. We have used the luminance intensity proportionality (LI%) to tackle the second problem.

A number of authors have found limitations with the use of cross-polarization. Robertson and Toumba recognized that there are two main problems with cross-polarized images. First, because the polarizing filter reduces the amount of light entering the lens, the object will be darker in the viewfinder, and a larger aperture is required to produce an acceptable picture. This will limit the depth of field or the range of sharpness of the image. Second, there is a loss of color balance, with a yellowing of the teeth, which may require some getting used to. The quality of images may be improved by the development of different light sources to illuminate the object. Investigators have recently found that images of skin lesions produced with a light-emitting diode illuminator were more reproducibly assessed than those produced using a conventional flash-assisted illumination because the intensive surface reflections were minimized.

Hill and Geddes were unimpressed with cross-polarization, which they used to record stains on the teeth using black-and-white film. They were unable to detect any lesions because the “prints appeared completely flat and lacking in contrast.” They concluded that cross-polarization was not suitable for photography of early caries lesions. Fleming et al also rejected cross-polarizing filters because they found them impractical to work with on location. In addition, they found it difficult to focus the image, and flash output was restricted. Apart from restricting the flash output, which was compensated for by increasing the size of the aperture, these problems were not encountered in this study. The polarizing filters added very little to the weight and complexity of the technique.

Robertson and Toumba found that their investigators considered 100% of the cross-polarized photographs as suitable for assessing enamel defects,
whereas only 10% of the nonpolarized photographs were considered suitable. The investigator in this study did notice a difference between images even though he was blind to which were polarized or not. He found the lesions on the PIs to be more clearly demarcated than on the NPIs, which might explain the improved reproducibility in the measurement of lesion area.

CONCLUSIONS

- The use of a cross-polarizing filter to reduce incidental flash reflection on digital images enhances the subjective assessment of demineralized lesions surrounding an orthodontic bracket and improves the reproducibility of measuring lesion area with computerized image analysis.
- There was no evidence that the use of a cross-polarizing filter improves assessment of the changes in enamel gray levels that occur with demineralization.

REFERENCES