Title
Dual SWIR Reflectance/Transillumination Imaging for Caries Detection

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Dual SWIR Reflectance/Transillumination Imaging for Caries Detection

by

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THESIS

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Dual SWIR Reflectance/Transillumination Imaging for Caries Detection
Chung (Wilson) Ng

Abstract:

Short wavelength infrared (SWIR) and near-infrared (NIR) imaging methods have been in development for almost two decades for dental use. Due to the high transparency of enamel in the NIR, separate novel imaging configurations such as occlusal transillumination and cross-polarization reflectance imaging have been discovered to be useful in imaging interproximal and occlusal lesions, respectively. Novel clinical probes capable of acquiring simultaneous SWIR reflectance and occlusal transillumination images of lesions on tooth proximal and occlusal surfaces have recently been developed at UCSF. The dual probe is 3D-printed, and the imaging system uses a SWIR camera and fiber-optic light sources that use SWIR light at 1300-nm for occlusal transillumination and SWIR 1450-nm light for reflectance measurements. Previously, this dual probe was used to image extracted teeth with proximal and occlusal lesions, showing promising results verifying false positives using micro-CT images as a gold standard to assess performance. The purpose of this study is to determine the sensitivity and specificity of this novel probe on 40 human test subjects each with 2-4 premolars scheduled for extraction due to orthodontic purposes. In addition to imaging with the dual probe, visible intraoral photos of the teeth were taken prior to extraction. After extraction, radiographs of the teeth were taken, and samples were imaged using microradiography serving as the gold standard. The visible digital images and radiographs were assessed, and all samples were scored with the standardized ICDAS criteria. For the short-wave infrared images, contrast calculations were performed. The sensitivity and specificity were then calculated for visual examination, radiography, individual SWIR reflectance and occlusal transillumination and for combined SWIR reflectance and occlusal transillumination. Our study demonstrates for the first time that near simultaneous transillumination (1300-nm) and reflectance (1600-nm) video can be successfully acquired of lesions in real-time. Both imaging modalities had markedly higher sensitivity for lesions on proximal and occlusal surfaces compared to conventional methods (visual and radiographic images). Reflectance imaging at 1600-nm had significantly higher specificity than transillumination at 1300-nm.

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1. Introduction:

Despite the introduction of fluoridated drinking water, fluoride dentifrices and rinses, and improved dental hygiene in the US, dental decay continues to be the leading cause of tooth loss even though caries progression is potentially preventable and reversible (especially if detected early) [19,20]. The locations of most newly discovered caries are on the occlusal pits/fissures of the posterior dentition and the interproximal contact sites between adjacent teeth, where radiographs have low diagnostic sensitivity [7] due to overlapping enamel and physical access is difficult, respectively. By the time the lesion is severe enough to appear on a radiograph, it typically has penetrated well into the dentin and surgical intervention is required [7]. Stains interfere with visual diagnosis and other proposed imaging technologies such as Fiber Optic Transillumination or fluorescence-based methods, often leading to false positives [8]. Likewise, early interproximal lesions can also be difficult to detect due to lack of physical access and challenge of radiographically identifying the initial, subtle mineral loss of these lesions [9]. A highly sensitive and more reliable method for detecting demineralization during early lesion formation would be valuable for clinicians to monitor the activity of new caries and to assess the efficacy of non-surgical intervention.

More than a decade ago, enamel was discovered to be highly transparent at longer wavelengths beyond the visible range (Figure 1) [1,21]. Based on that knowledge, the Fried Lab demonstrated the high potential of the NIR (700- 1000-nm) and SWIR (1000-2500-nm) for imaging caries lesions and that novel imaging configurations such as occlusal transillumination and cross-polarization reflectance imaging (Figure 2) can be used to image lesions on both occlusal and proximal surfaces [2,3,4].

Short wave infrared imaging (SWIR) has been shown to provide higher diagnostic performance than radiographs to detect the types of lesions noted above, without exposing patients to ionizing radiation which allows for more frequent monitoring of lesions [22]. In addition, highly conjugated molecules produced by bacteria such as melanin and porphyrins and found in food and drinks, accumulate in dental plaque and are responsible for the pigmentation in the visible range [23]. These molecules do not absorb light beyond 1200-nm [24]. Hence, images acquired using SWIR reflectance measurements are free of interference from stains beyond 1200-nm [8] and the lesion contrast provides a quantitative measure of demineralization to be used for monitoring the severity of the lesion over time.

Despite this knowledge, multiple commercial NIR clinical imaging devices have been introduced that operate at relatively lower wavelength than is optimal, such as the CariVu (Dexis, Hatfield, PA) which uses NIR occlusal transillumination with 780-nm light and the Vistacam IX (PROXI) from Durr Dental (Bietigheim- Bissingen, Germany) which uses NIR reflectance at 850-nm [25,26]. Imaging at shorter NIR wavelengths near 830 nm was investigated more than a decade ago. The 830-nm system was capable of higher performance than visible systems, but the contrast was significantly lower than that attainable at high wavelengths such as 1300 nm and simulated lesions could not be imaged through the full enamel thickness due to greater light scattering. In addition, it appears that stains are still visible at the shorter NIR imaging systems, where commercial systems are now operating.

Although the availability of such commercial devices represents a step forward in the right direction, systems operating at longer wavelengths should be capable of much higher performance due to the higher transparency of dental hard tissues at longer wavelengths (Figure 1) and the transparency of stains at wavelengths beyond 1200-nm. The development of multispectral and multimodal imaging approaches to reduce the potential for false positives and improve diagnostic performance are highly innovative and clinically feasible. In a recent clinical study [10] with three imaging probes operating at 1300-nm and 1500-1700-nm, Simon et al. achieved higher diagnostic performance in aggregate than radiographs for lesions on both proximal and occlusal surfaces of 109 teeth. The diagnostic performance of each individual probe alone was equal to or slightly higher than radiographs for lesions on proximal surfaces, and all were higher for occlusal lesions. The teeth were collected, sectioned, and examined with polarized light microscopy and transverse microradiography which served as the gold standard. In addition, extra-oral radiographs were taken of teeth and the diagnostic performance of near-IR imaging was compared with radiography. Near-IR imaging was shown to be significantly more sensitive than radiography for the detection of lesions on both occlusal and proximal tooth surfaces in vivo.

However, a major concern with the higher sensitivity of SWIR imaging is the potential for false positives that may lead to unnecessary cavity preparations. We hypothesize a combined reflectance and transillumination probe, such as the one that will be used for this study, will reduce false positives since confounding structural features or specular reflection are unlikely to be present in both reflectance and transillumination images. In addition, the dual probe may provide complementary diagnostic information about lesion severity to help discriminate early superficial lesions on tooth surfaces from deeply penetrating lesions. Since both the reflectance and the occlusal transillumination probes sample light emitted from tooth occlusal surfaces, it is therefore feasible to combine both methods into a single probe that can be positioned above the tooth for practical and rapid clinical screening.

2. Central Hypothesis:

We hypothesize that a dual handheld multispectral and multimodal SWIR probe, combining both transillumination and reflectance, will clinically demonstrate a higher diagnostic performance than radiography for early demineralization on occlusal and proximal surfaces by reducing false positives and offering higher specificity.

3. Specific Aims:

Our first aim is to demonstrate that a combined reflectance and transillumination probe will have higher sensitivity and specificity to identify early lesion presence than radiographs in-vivo.

Our second aim is to determine whether the dual probe will provide diagnostic information about lesion severity to aid in discriminating early superficial lesions on tooth surfaces from deeply penetrating lesions.

4. Materials and Methods:

4.1 Subjects and Samples:

This study utilizes orthodontic patients (12-60 years) who require removal of 2-4 premolars that have been fully erupted for at least a year for orthodontic reasons. Test subjects were recruited from the UCSF Orthodontic clinic by the Orthodontic residents. There was no cost to the subject for participating in the study. Patients were expected to pay the ordinary and usual fee for the previously scheduled tooth removals for their routine dental care. Subjects were reimbursed at a rate of $200.00 at the time of tooth extraction. After in-vivo imaging is completed, the teeth were extracted at the UCSF Periodontology Clinic. These collected teeth will be sterilized by Gamma Irradiation and subsequently sectioned for histological examination with polarized light microscopy and microradiography.

4.2 Dual SWIR probe:

The dual probe design consists of a reflectance probe body and a transillumination attachment, shown in Figure 3 [5]. The reflectance probe body and the transillumination attachment were 3D printed and are autoclavable. There is an air nozzle near the mirror to prevent fogging of the mirror. The air nozzle can also be used to dry the lesion to increase lesion contrast and potentially assess lesion activity.

4.3 Image Acquisition and Analysis

Visible images of each tooth prior to extraction were acquired using an intraoral camera. SWIR images of each premolar tooth were also acquired using the multispectral dual SWIR probe. After extraction, radiographs of the teeth were captured, and they were imaged using micro-CT which serves as the gold standard. One clinician examined the visible digital images and radiographs independently, and all ROIs were traced from the SWIR images. For calculating contrast of occlusal lesions from SWIR images, the occlusal fissure was selected as the area of interest (Figure 11). Lesion intensity is selected as the average intensity of occlusal fissure, and sound enamel intensity was selected as the average intensity of adjacent pixels near the lesion. For calculating contrast values of interproximal lesions from SWIR images, the lesion intensity is selected as the average intensity of the interproximal contact and the sound enamel intensity is selected as the average intensity of adjacent pixels near the lesion (Figure 12).

The average contrast of lesions found on radiographs identified by the clinician, of lesions found in reflectance images, and of lesions found in transillumination images, were calculated using formulas summarized from Figure 4. Since the lesions appear bright in the reflectance imaging modality (rather than appearing dark in transillumination or radiographs), the formula to calculate contrast has been adjusted accordingly. Two-tail T-tests were conducted to determine the statistical significance of contrasts values of radiographs, SWIR reflectance, and SWIR transillumination imaging.

Once this average contrast of positive radiographic detection was calculated, this same value served as the positive contrast threshold for the SWIR imaging modalities. If contrast for the SWIR imaging is larger or equal to than the average contrast of positive radiographic detection, then a positive detection on the SWIR ROI was recorded. If contrast is smaller than the average contrast of positive radiographic detection, then a negative detection on the SWIR ROI was recorded.

Teeth were be scored with the standardized ICDAS criteria. Two proximal surfaces and one occlusal surface per tooth were scored. Surfaces were scored as 0-4 for radiographs, SWIR and μCT with 0-sound, 1- outer half of enamel, 2- inner half of enamel, 3- outer half of dentin and 4- inner half of dentin.

The sensitivity and specificity were calculated for visual examination, radiography, individual SWIR reflectance and occlusal transillumination and for combined SWIR reflectance and occlusal transillumination.

5. Results:

5.1 Samples

A total of 40 patients were recruited from UCSF Orthodontics clinic. Total number of teeth scanned is 135. However, 24 teeth were excluded from the final analysis for the following reasons: pre-existing composite restorations were interfering with ROIs (regions of interest), bonding adhesive interfering with ROIs, tooth restored with composite after imaging, severely damaged or decayed tooth, or corrupted imagine files. Hence, the total number of teeth that were included for the final analysis totaled 111. Since each sample has three ROIs (i.e., occlusal surface, mesial proximal surface, distal proximal surface), the total number of ROIs included for analysis is 333.

5.2 Micro-CT Statistics

The 333 ROIs were categorized based on surface type (sound tooth structure, enamel lesions, dentinal lesions, cracks, cavitations) and surface location (occlusal, mesial, distal. Micro-CT identified 24 occlusal surfaces, 88 mesial proximal surfaces, and 75 distal proximal surfaces as sound tooth structure. There were 75 occlusal enamel lesions, 16 mesial enamel lesions, and 30 distal enamel lesions. Dentinal lesions were found on 11 occlusal surfaces, 1 mesial surface, and 1 distal surface. Cracks were found on 1 occlusal surface, 6 mesial surfaces, and 4 distal surfaces. One single distal cavitation was discovered by the Micro-CT analysis.

5.3 Radiographs Analysis and Positive Contrast Threshold

Of the 111 teeth that were included in the study, 9 lesions were identified from the clinician's examination of radiographs. The contrast of each lesion was calculated with the formula from Figure 4, and the average contrast was determined to be 0.12 (Figure 5). This value was used as the positive contrast threshold for both reflectance and transillumination SWIR imaging modalities. If contrast for the SWIR imaging was larger or equal to than 0.12, then a positive detection was recorded. If contrast the SWIR imaging was smaller than 0.12, then a negative detection was recorded.

5.4 SWIR Occlusal Lesion Contrast

As noted in section 5.2, a total of 86 occlusal lesions (enamel and dentinal) was identified from MicroCT. The average contrast for occlusal lesions from the reflectance imaging modality was statistically significant, at an average contrast of 0.18 (Figure 6). The average contrast for occlusal lesions from the transillumination imaging modality was also statistically significant, at an average contrast of 0.15 (Figure 7).

5.5 Sensitivity and Specificity for Occlusal Detection of all Individual Imaging Modalities

Contingency tables (Table 1) were constructed for each of the four imaging modalities individually (Table 2). Sensitivity for reflectance and transillumination were calculated to both be 0.66. Sensitivity of visual images and radiographs were 0.12 and 0.01, respectively. The specificity for reflectance and transillumination were 0.96 and 0.57, respectively. These values are summarized in Table 3. A contingency table (Table 4) was constructed for combining both reflectance and transillumination imaging modalities as a single category, which was labelled as “combined” SWIR imaging. The combined SWIR sensitivity was 0.41, and its specificity was 1.0 (Table 5).

5.6 SWIR Interproximal Lesion Contrast

As noted in section 5.2, a total of 49 interproximal lesions (enamel and dentinal) was identified from MicroCT. The average contrast for interproximal lesions from the reflectance imaging modality was statistically significant, at an average contrast of 0.175 (Figure 8). The average contrast for interproximal lesions from the transillumination imaging modality was 0.14 (Figure 9).

5.7 Sensitivity and Specificity for Interproximal Detection of all Individual Imaging Modalities

Contingency tables were constructed for each of the four imaging modalities individually (Table 6). Sensitivity for reflectance and transillumination were calculated to both be 0.56 and 0.58, respectively. Sensitivity of visual images and radiographs were 0.02 and 0.07, respectively. The specificity for reflectance and transillumination were 0.93 and 0.70, respectively. These values are summarized in Table 7. A contingency table (Table 8) was constructed for combining both reflectance and transillumination imaging modalities as a single category, which was labelled as “combined” SWIR imaging. The combined SWIR sensitivity for interproximal lesions was 0.30, and its specificity was 0.93 (Table 9).

5.8 Occlusal Lesion Severity: Contrast Analysis

Based only on SWIR contrast, there is no significant difference between contrast between enamel and dentinal occlusal lesions for either reflectance or transillumination imaging modalities (Figure 10).

6. Discussion:

The posterior occlusal surfaces and interproximal surfaces between adjacent posterior teeth are challenging areas to detect early demineralization, since enamel is overlapped at the occlusal surface and traditional bitewing radiography has a low sensitivity for detection of early proximal lesions that extend only into enamel. Visual detection of early demineralization on occlusal surfaces may also be confounded by staining in the occlusal fissures that make it difficult for clinicians to accurately pinpoint the areas of demineralization. Stains also tend to make an early lesion appear more severe than it may in fact be. A thorough and complete removal of all stain from the pits and fissures is not always clinically feasible.

Current NIR imaging devices on the market for caries detection operate at 780 and 850 nm, where studies show that there is significant interference from stains. In addition, the contrast between sound and demineralized tooth structure has previously been shown to be markedly higher at longer NIR wavelengths than it is at 850 nm. The primary disadvantage of operating at longer NIR wavelengths is that Si-based imaging technologies are only efficient at wavelengths under 1000 nm. Alterative imaging technologies such as InGaAs and Ge-enhanced Si are still expensive. The limited use of these more innovative semiconductors technologies is a major reason for the high cost. However, with expanded use, those prices are expected to decrease. The cost has decreased significantly in the past 10 years and the performance has increased markedly.

Prior studies have demonstrated that occlusal transillumination and reflectance imaging modalities using longer wavelengths (e.g. in the short-wave infrared spectrum) may offer higher sensitivity regarding early lesion detection, but each individual imaging modality on its own has low specificity and can lead to false positives. We demonstrated in this study that it is in fact possible to capture near-simultaneous transillumination (1300-nm) and reflectance (1600-nm) video of lesions successfully in vivo and in real-time, which has not been done prior to this study. Both imaging modalities, whether considered separately or when combined, had higher sensitivity (Table 3 and Table 5) for lesions on both proximal and occlusal surfaces compared to conventional methods, such as visual and radiographic. In the past, some concerns have been raised that technologies with a higher sensitivity to detecting lesions may lead potentially to “overtreatment” or more invasive dentistry being performed than needed. However, it’s important to keep in mind that the operating clinician should bear the responsibility to make clinical judgements based on the data and the current evidence. Higher sensitivity in detecting early lesions should be advantageous because clinicians can intervene with minimally invasive techniques earlier to prevent such lesions from progressing until a surgical intervention is needed. Regarding specificity, reflectance imaging at 1600-nm had a marked significantly higher specificity than transillumination imaging at 1300-nm.

With its high sensitivity and high specificity, SWIR reflectance imaging at 1600-nm as a standalone modality could potentially be a useful adjunct for clinicians to help detect early demineralization. Additional analysis needs to be performed to better assess the advantages of the combined imaging approach, to determine (1) whether combining both imaging modalities is necessary with the advantages of reflectance imaging alone and (2) to determine if additional information may be garnered about lesion severity from other factors such as size and shape of the lesions on the SWIR images, given that contrast values alone did not correlate to the depth of lesions from this study's results.

This study suggests that SWIR Imaging methods offer high sensitivity for lesions on proximal and occlusal surfaces without the interference of stains that occurs at wavelengths less than 1100-nm. No SWIR methods are currently available in the commercial market due to high cost and security concerns, but we anticipate that this innovative technology will increasingly become more accessible for medical use.

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Figures

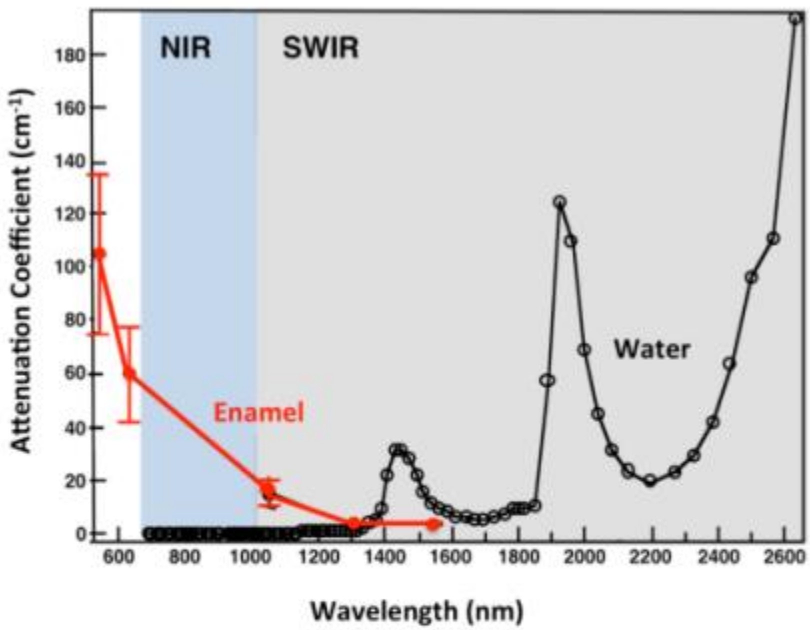

Figure 1. The attenuation coefficient for dental enamel (red) and the absorption coefficient of water (black) in the visible to IR. NIR range is 700-1000nm (blue) and SWIR range is 1000-2500nm (gray).

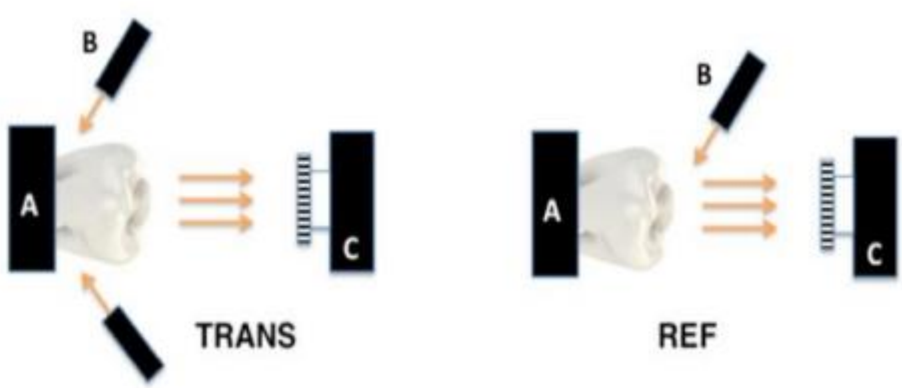

Figure 2. Imaging configurations for (TRANS) SWIR occlusal transillumination and (REF) cross-polarized SWIR reflectance with (A) tooth, (B) light source, and (C) camera.

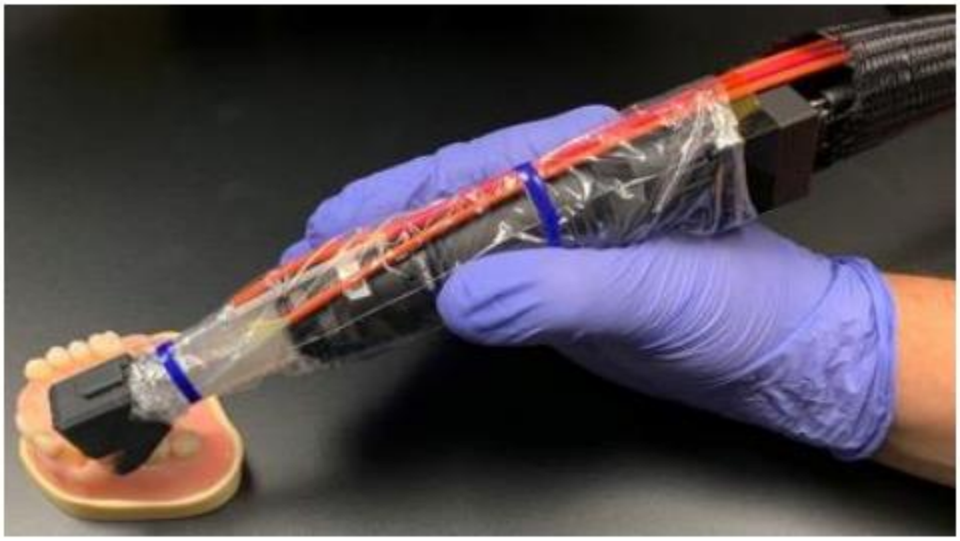

Figure 3. Dual SWIR transillumination/reflectance imaging handpiece.

$$\text{Contrast}_{\text{x-ray}} = \left| \frac{\text{Sound Enamel Intensity - Lesion Intensity}}{\text{Sound Enamel Intensity}} \right|$$

$$\text{Contrast}_{\text{ref}} = \frac{\text{Lesion Intensity} - \text{Sound Enamel Intensity}}{\text{Lesion Intensity}}$$

$$\text{Contrast}_{\text{trans}} = \left| \frac{\text{Sound Enamel Intensity - Lesion Intensity}}{\text{Sound Enamel Intensity}} \right|$$

Figure 4. Contrast calculations for radiographs, reflectance, and transillumination.

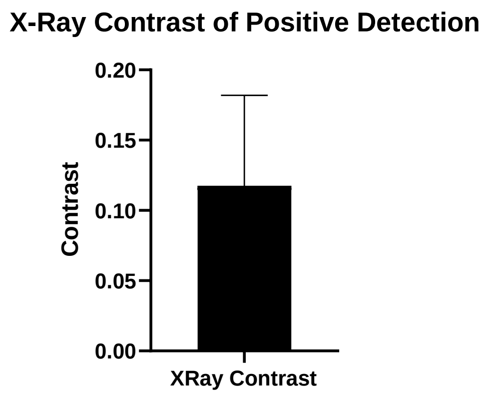

Figure 5. Contrast of radiographs of positive detection.

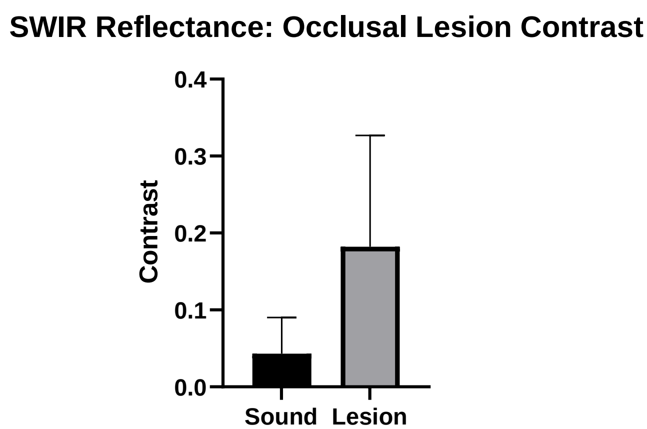

Figure 6. Occlusal Lesion Contrast in SWIR reflectance imaging.

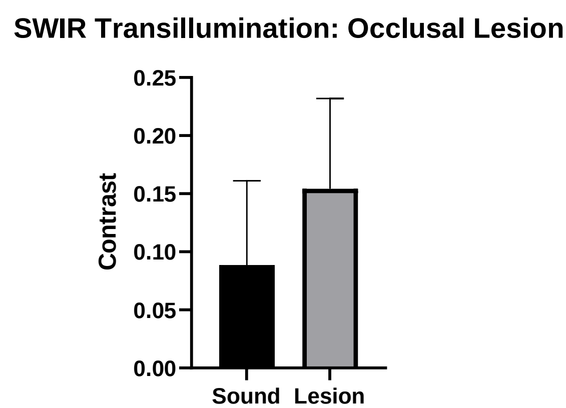

Figure 7. Occlusal Lesion Contrast in SWIR transillumination imaging.

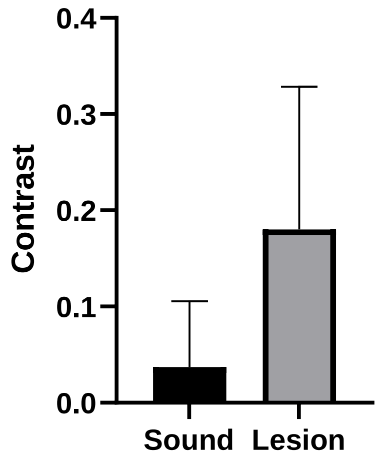

Figure 8. Interproximal Lesion Contrast in SWIR reflectance imaging.

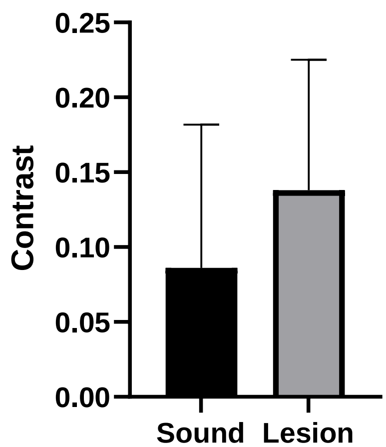

Figure 9. Interproximal Lesion Contrast in SWIR transillumination imaging.

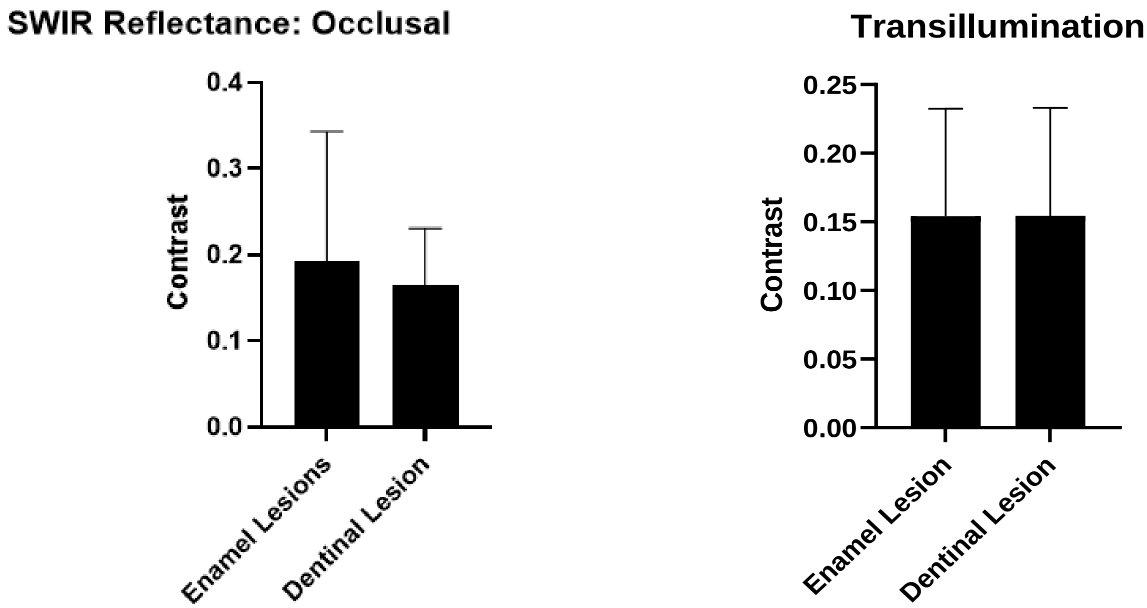

Figure 10. Contrast between enamel and dentinal occlusal lesions for reflectance and transillumination imaging.

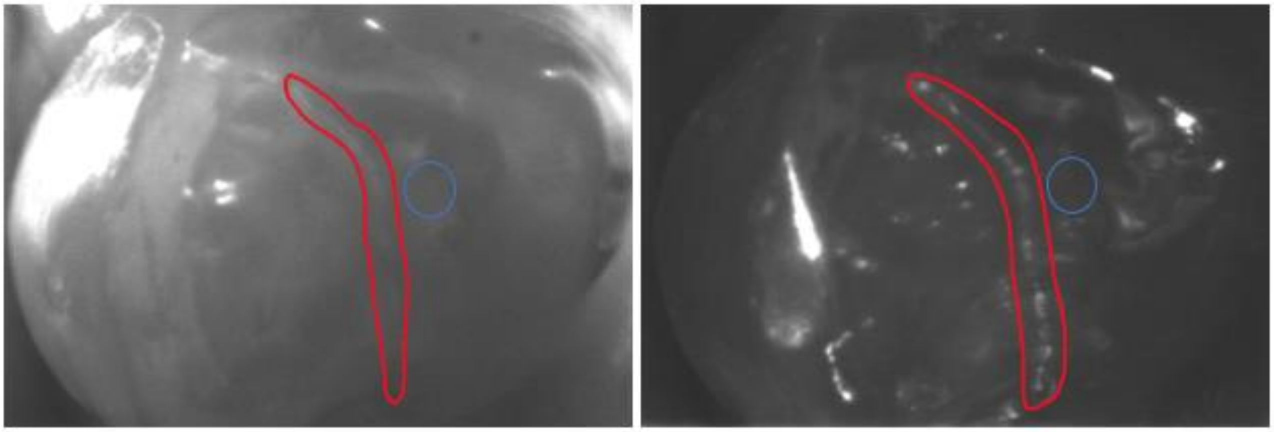

Figure 11. SWIR contrast calculation for Occlusal ROIs. Lesion intensity (red) is selected as the average intensity of the occlusal fissure. Sound intensity (blue) is selected as the average intensity of adjacent pixels near the lesion.

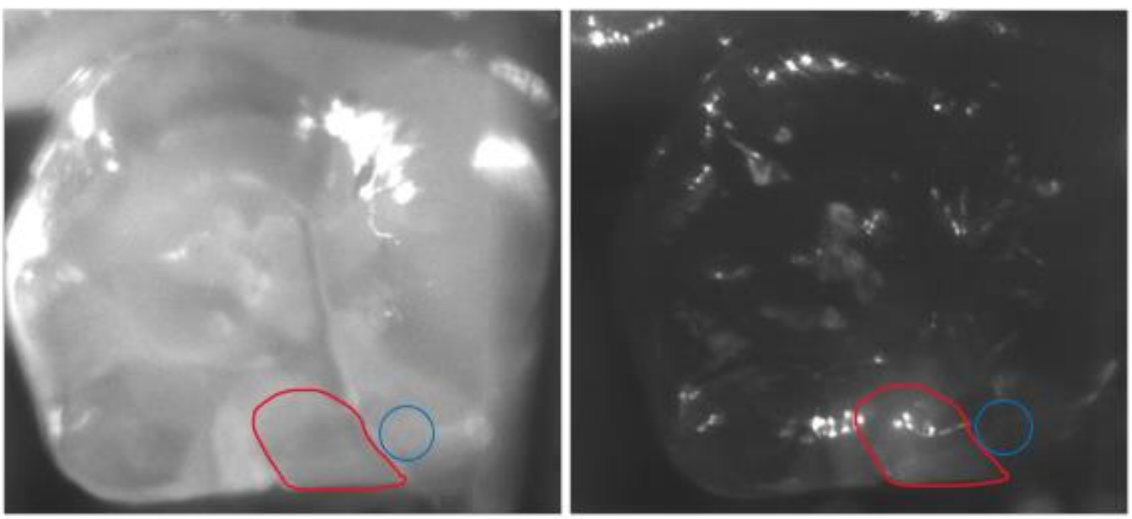

Figure 12. SWIR contrast calculation for Interproximal ROIs. Lesion intensity (red) is selected as the average intensity of the interproximal contact. Sound intensity (blue) is selected as the average intensity of adjacent pixels near the lesion.

Tables

Table 1. Contingency Table

Predicted Values \ Actual Values	Positive (1)	Negative (0)
Positive (1)	TP	FP
Negative (0)	FN	TN

Table 2. Occlusal Lesion Detection Rates

Visual	Positive	Negative
Positive	10	8
Negative	76	16

Radiograph	Positive	Negative
Positive	1	1
Negative	85	23

Reflectance	Positive	Negative
Positive	57	1
Negative	29	23

Transillumination	Positive	Negative
Positive	53	13
Negative	27	17

Table 3. Occlusal Lesions Sensitivity and Specificity Values for reflectance, transillumination, visual, and radiographs.

	Reflectance	Transillumination	Visual	Radiograph
Sensitivity	0.66	0.66	0.12	0.01
Specificity	0.96	0.57	0.67	0.96

Table 4. Occlusal Lesions Contingency table for combining both reflectance and transillumination imaging modalities.

Combined	Positive	Negative
Positive	35	0
Negative	51	24

Table 5. Occlusal Lesions Combined SWIR sensitivity and specificity.

	Visual	**Radiograph**	**Combined**
Sensitivity	0.12	0.01	0.41
Specificity	0.67	0.96	1.00

Table 6. Interproximal Lesion Detection Rates.

Visual	Positive	Negative
Positive	1	0
Negative	58	163

Radiograph	Positive	Negative
Positive	4	0
Negative	55	163

Reflectance	Positive	Negative
Positive	33	12
Negative	26	151

Transillumination	Positive	Negative
Positive	34	49
Negative	25	114

Table 7. Interproximal Lesions Sensitivity and Specificity Values for reflectance, transillumination, visual, and radiographs.

	Reflectance	Transillumination	Visual	Radiograph
Sensitivity	0.56	0.58	0.02	0.07
Specificity	0.93	0.70	1.00	1.00

Table 8. Interproximal Lesions Contingency table for combining both reflectance and transillumination imaging modalities.

Combined	Positive	Negative
Positive	14	12
Negative	32	164

Table 9. Interproximal Lesions Combined SWIR sensitivity and specificity.

	Visual	Radiograph	Combined
Sensitivity	0.02	0.07	0.30
Specificity	1.00	1.00	0.93

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