Cross-polarization optical coherence tomography (CP-OCT) is a promising imaging modality to detect demineralization under the margins of composite restorations. The aim of this study was to assess how base materials applied under composite resin may affect CP-OCT image assessment. Base materials are commonly used for managing deep dentinal decay but once applied residual amounts of the base materials can be inadvertently left on the inner enamel walls. This study determined that base materials have significantly different scattering properties. The order grouping in the mean backscattered reflectivity (mR) of the base material was Dycal>caries phantom>Fuji IX, Vitrebond, Fuji II (p<0.05). The calcium hydroxide base (Dycal) had a higher mR than demineralized dentin and Vitrebond before and after the resin restoration was placed (p<0.05). While calcium hydroxide maybe a confounder in CP-OCT imaging, several protective base materials are compatible with this type of imaging modality.

Keywords: Optical coherence tomography, Diagnostic imaging, Dental materials, Teeth, Dentistry

INTRODUCTION

Porosities that are caused by demineralization can drastically alter the optical properties in enamel and dentin. For clinicians, this change in mineral volume appears visually as a white spot lesion. This change of translucency toward a more opaque and backscattering (up to 4 mm in depth) can aid in differentiating near surface demineralization from sound tissue. In controlled studies, CP-OCT has been shown to assess changes to tooth mineral volume by measuring direct changes in backscattered reflectivity during and after polymerization shrinkage. This allows OCT to be vital in understanding material science properties like shrinkage stress and gap formation. OCT can image the real-time gap formation during and after polymerization shrinkage. Despite differences between OCT and CP-OCT, there is a clear benefit of non-polarized system over CP-OCT that minimizes the effects of gaps. CP-OCT benefit is that non-carious structural defects like gaps are not erroneously identified as carious. A polarized sensitive system that captures both polarization states is ideal, but the cost of a fast acquisition Fourier domain OCT system remains prohibitive for clinical practice.

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The effect of base material composition on demineralization assessment in CP-OCT dental imaging

Anna SIPE and Robert S. JONES

Division of Pediatric Dentistry, Department of Developmental and Surgical Sciences, School of Dentistry, University of Minnesota, Minneapolis, MN, USA
Corresponding author, Robert S. JONES; E-mail: rsjones@umn.edu
protective base materials to address post-operative sensitivity and when the extent of the demineralization/decay is extensive. These base materials can also be inadvertently applied to the inner enamel walls during placement. The optical properties of these bases have not been investigated. The main aim of this study was to assess the effect of base materials on detecting the secondary caries using the CP-OCT.

MATERIALS AND METHOD

CP-OCT
A Cross-Polarization Swept Source Optical Coherence Tomography (CP-OCT) System (IVS-200-CPM, Santec Komaki, Japan) with a dental intraoral probe was used to image our composite material samples. An advantage of using CP-OCT for imaging composite samples is that surface reflections and interfacial reflections (gaps) are filtered out significantly and this reduces their confounding effects on assessing demineralization below the interface. The portable CP-OCT system used a high swept rate (30 kHz) continuous wavelength scanning laser centered near 1,310 nm with a bandwidth of 104 nm. The axial resolution for structures was 8.5 µm. The lateral resolution of the system was ~80 µm. The higher than ideal lateral resolution was required since the system has a fixed depth of focus. A low numeric aperture (NA) lens was necessary to maximize the depth of field for the occlusal topography in the intraoral cavity. The output beam from the swept source traveled in single-mode fiber and then was split to a sample and reference arm that was housed in intraoral dental scanning probe. In the sample arm, the output signal traveled through a collimator system and traveled through a polarizing beam splitter. The output wave was linearly polarized in the P-polarization state. In order to control the polarization states of the light in the reference and sample arms and produce an optimum interference pattern, polarization controllers were used. Light then traveled through a fixed focusing lens (f=60) and was reflected onto a two-axis tilt micro-electro-mechanical system (MEMS) scanning mirror in the body of the probe. The MEMS mirror collected two-dimensional images. The linearly polarized output beam was reflected at the probe end to illuminate (~8 mW) a material sample. The backscattered signal from the sample traveled back through the probe and the polarizing beam splitter. At this point, the S-polarization state (cross-polarization of the incident beam) was diverted to recombine with the reference signal. The polarization suppression was previously measured to be 31.4 dB indicating that over 99.9% of the reflected light in the P-polarization state does not recombine with the reference signal. Interferometric concepts of swept source OCT imaging and images of the interferometer set-up are described elsewhere.

Composite disc model—An enamel caries model
Since residual base material can inadvertently be placed on the inner enamel walls near the DEJ, we used an existing enamel caries model to examine the influence of base materials on CP-OCT imaging. This composite disc model is also a precise and high throughput model. We used a previously validated method for assessing the optical properties through resin composite discs. In this study, we examined four different base materials (total n=24; sample n=6) under resin composite discs. Four different base materials (Dycal, Fuji IX, Fuji II LC, Vitrebond) were studied. Dycal (Dentsply Sirona, York, PA, USA) is a protective base liner composed of calcium hydroxide, zinc oxide, titanium oxide, and Disalicylate ester of 1,3 butylene glycol. Fuji IX (GC Tokyo, Japan) is traditional glass ionomer. Fuji II LC (GC Tokyo) and Vitrebond (3M, St. Paul, MN, USA) are both resin-modified glass ionomers. A layer of base material (0.5 mm thick) was inset in the disc where the based was under 1.8 mm of resin composite (Fig. 1a). To standardize the assessment of the optical properties of the base materials, a single type of dental resin composite material was used. Based on previous work, IPS Empress Direct Enamel (Shade B2, Ivoclar Vivadent, Schaan, Lichtenstein) was an ideal resin composite for CP-OCT imaging due

Fig. 1 Disc model experimental set-up.

1. Composite Disc 2. Base Material Inset

a) The Disc Model

b) Directly Measuring Base Material Scattering

There is a slight offset so that CP-OCT can image the caries phantom directly

There is a slight offset so that CP-OCT can image the caries phantom directly

C Base Material Scattering Under Composite

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to good visual esthetics (not too visually translucent) but has a high translucency at 1,310-nm with minimal depolarization effects\(^2\). Resin composite and base material discs had 30 s of cure time with a halogen light source (QHL75, Dentply Sirona, York, PA, USA) between glass slides to eliminate the need for further polishing.

Hydroxyapatite discs (HA, Clarkson Chromatography, South Williamsport, PA, USA) were placed under the composite discs. HA discs have the same chemical composition as dental tooth enamel but the sintered material makes the material scatter light similar to demineralized tooth enamel\(^2\). CP-OCT imaged through the composite discs with underlying base material. These composite discs were also imaged with the disc flipped and imaged with the base material facing up so that the difference between the optical signals (base versus base under the resin composite) could assess the overall attenuation of the base signal (Fig. 1b).

**Tooth composite model** — **Dentinal caries model**

The next stage of the study was to create a CP-OCT imaging model for secondary dentinal caries. In this model, in vitro extracted teeth with definitive cavitated lesions were included in the study and prepared. Residual soft dentin, which was determined through a sharp dental explorer, was intentionally left. The goal of this model was to compare the scattering properties of ‘soft’ dentin demineralization to higher scattering base materials. In the previously mentioned composite disc model, we screened several bases and compared the results to an enamel caries phantom model. In this stage of the study, we used extracted teeth that were extracted and collected as pathological specimens (IRB exempt study 1002E77235-45 CFR Part 46.101(b) category #4). The oral surgery department extracts teeth for several reasons besides extensive caries, such as for periodontal reasons or due to insufficient space for third molars. Sound teeth were also available in the de-identified collection of pathological specimens. Carious and sound teeth were used to test the two bases (n=66; n=22 in each base group), and teeth were prepped with a high-speed handpiece by a dentist at a targeted depth of 2.5 mm. Near infrared CP-OCT has an optimal imaging depth between 2–3 mm\(^2\). After the carious teeth were prepared, residual dentin demineralization was intentionally left. CP-OCT imaged the preparation prior to the restoration. Teeth were then etched (15 s-35% phosphoric acid), rinsed with water, and blotted dry. Two successive coats of 3M™ ESPE™ Adper Single Bond Plus Dental Adhesive System (3M) was applied to the teeth for 15 s followed by 10 s light cure. A dental resin composite (IPS Empress Direct Enamel B2, Ivoclar Vivadent) was placed into the cavity preparation and cured for 30 s. After the sound teeth were prepared, the two base materials were added as a thin layer. CP-OCT imaged this base layer before resin composite was added. Teeth were restored with resin composite as described.

**Image and statistical analysis**

Image analysis was performed using custom programs written in Matlab™ (Mathworks, Natick, MA, USA) to calculate the mean integrated backscattered reflectivity (mR) of the base, HA, and dentinal demineralization alone and underneath the composite material\(^8\). The mean intensity of the backscattered signal in air (background) measured the dB offset, and the values reported in this study are adjusted by subtracting the dB offset value so that the signal in air is zero. The parameter mR was calculated by integrating the reflectivity over a 500×500 µm section and then dividing by the overall section dimension. The mR of the materials were measured before and after the composite restoration. The %T parameter is the mR of the material under the composite divided by the mR of the material measured before the resin composite was placed. The parameter %T examines the ability to differentiate materials versus carious structures based on the scattering of an underlying structure. The parameter %T is dependent on the translucency of the resin composite, which was optimized based on previous work\(^2\). In order to get an accurate %T, serial imaging is required. CP-OCT has to image the same region of the tooth before and after the composite is added. A custom mounting jig was created for the teeth to be removed and replaced at the same location (Figs. 2a–c). Statistical analysis was performed in MedCalc (version 13.1.2, Ostend, Belgium).

**RESULTS**

CP-OCT images of the resin discs with the base materials (Figs. 3a–d) facing the CP-OCT imaging probe illustrates the inherent scattering properties of the base material relative to the caries scattering phantom (compressed powder HA disc) and the resin composite of IPS Empress Direct Enamel B2. The grayscale CP-OCT images displays high scattering as white and low scattering as black. The calcium hydroxide base material (Dycal) is visually an off white opaque material and the
ICP-OCT images of the composite discs with the underlying base materials facing up in order to assess the inherent scattering of the base material. The mean backscattered reflectivity (mR) is assessed by taking a mean value of a sampled region (boxed area). Each of the boxed areas samples a different region of the composite disc model. The base material is on the right side. e–h) when the composite discs are flipped upward where the base is under ~1.8 mm of resin composite (right side of images), the mR of the base materials can be assessed. This combined approach of imaging the disc on both sides allows calculating the %T of the base under the resin composite.

Table 1  Mean backscattered reflectivity (mR) of the hydroxyapatite caries phantom (enamel caries) and the base materials (n=6 per sample) both direct (step 1) and under (U) the resin composite (step 2)

| Step 1: Direct imaging base in disc model | Group # | Name     | Mean (dB) | 95% CI     | SD  | Different from Group (p < 0.05) |
|-----------------------------------------|---------|----------|-----------|------------|-----|--------------------------------|
| a                                       | Caries Phantom | 28.89    | 28.63–29.15 | 0.32   | (b)(c)(d)(e)                  |
| b                                       | Dycal   | 32.36    | 31.23–33.48 | 1.07 | (a)(c)(d)(e)                  |
| c                                       | Fuji IX | 19.72    | 18.76–20.68 | 0.91   | (a)(b)(d)                     |
| d                                       | Fuji IILC | 15.53   | 14.84–16.22 | 0.66   | (a)(b)(c)(e)                  |
| e                                       | Vitrebond | 20.62   | 19.00–22.24 | 1.54   | (a)(b)(d)                     |

| Step 2: Imaging through composite disc with underlying base | Group # | Name    | Mean (dB) | 95% CI    | SD  | Different from Group (p < 0.05) |
|------------------------------------------------------------|---------|----------|-----------|----------|-----|--------------------------------|
| t                                           | Caries Phantom | 9.33    | 8.38–10.29 | 2.26 | (v)(x)(y)(z)                  |
| v                                           | Dycal   | 13.95   | 11.60–16.29 | 2.23 | (t)(x)(y)(z)                  |
| x                                           | Fuji IX | 5.23    | 4.08–6.37  | 1.09   | (t)(v)                        |
| y                                           | Fuji IILC | 2.07    | 0.96–3.18  | 1.06   | (t)(v)                        |
| z                                           | Vitrebond | 2.58    | 0.73–4.42  | 1.76   | (t)(v)                        |

CP-OCT image (Fig. 3a) shows that the material has a high backscattered scattering intensity near 1,310-nm (the center wavelength of the incident light of the CP-OCT). The glass ionomer base material (Fuji IX) is visually a white opaque material and the CP-OCT image (Fig. 3b) shows the material to display a higher scattering than the resin composite but lower scattering than the scattering of the caries phantom and calcium hydroxide base (Dycal) material. Both resin modified glass ionomer materials (Fuji II LC and Vitrebond) are visually off white, while CP-OCT imaging shows their scattering properties to be lower than that of the caries phantom and the calcium hydroxide base (Dycal). The image and statistical analysis of the mean backscattered reflectivity of the material discs are shown in Table 1. An analysis of variance (ANOVA, p < 0.001) and multiple testing (Tukey-Kramer, p < 0.05) provided the order grouping in the mean backscattered reflectivity (mR) of the materials: Dycal>caries phantom HA disc>Fuji IX, Vitrebond>Fuji IILC. When the material disc was...
flipped and the base material is under 1.8 mm of resin composite of IPS Empress Direct Enamel, CP-OCT images (Fig. 3e–h) show how the incident beam propagates through the translucent resin composite to capture the underlying signals of the base material. While the resin composite is translucent, the forward propagating and returning backscattered near infrared light is still slightly attenuated. For the materials under the resin composite (Table 1), an analysis of variance (ANOVA, \( p<0.001 \)) and multiple testing (Tukey-Kramer, \( p<0.05 \)) provided the order grouping in the mean backscattered reflectivity (mR) of the materials: Dycal>caries phantom HA disc>Fuji IX, Vitrebond, Fuji II LC. Under the resin composite, the glass ionomer and resin modified base

![Fig. 4 CP-OCT imaging in the tooth-composite model.](image)

a) sound tooth was prepared with high speed bur (#330). b) image of the calcium hydroxide based material Dycal. Sampled box areas represent a sampling of the air for background dB offset and the signal from the base material. c) the jig mounting of the sample allows repeated imaging of the same area after resin composite was placed. d–f) are images of the Vitrebond base added to a sound prepared tooth. g) natural carious dentin is intentionally left and CP-OCT was used to assess the before and after resin composite placement.

Table 2  Mean backscattered reflectivity (mR) of the dentinal caries, Dycal, and Vitrebond (\( n=22 \) per sample) before and after (U-under) the resin composite restoration was placed in the cavity preparation

| Group # | Name                  | Mean (dB) | 95% CI       | SD   | Different from group (\( p<0.05 \)) |
|---------|-----------------------|-----------|--------------|------|-----------------------------------|
| 1       | Dentinal Caries       | 17.33     | 15.71–18.95 | 3.66 | (2)(3)(4)(5)(6)                   |
| 2       | Dycal                 | 29.78     | 28.96–30.60 | 1.85 | (1)(3)(4)(5)(6)                   |
| 3       | Vitrebond             | 14.38     | 12.72–16.04 | 3.75 | (1)(2)(3)(5)                      |

Step 2: CP-OCT imaging of final restoration with underling caries or base

| Group # | Name                  | Mean (dB) | 95% CI       | SD   | Different from group (\( p<0.05 \)) |
|---------|-----------------------|-----------|--------------|------|-----------------------------------|
| 4       | Dentinal Caries       | 1.52      | 0.55–2.49    | 2.19 | (1)(2)(3)(5)                      |
| 5       | Dycal                 | 13.86     | 12.28–15.43  | 3.56 | (1)(2)(4)(6)                      |
| 6       | Vitrebond             | 3.23      | 2.38–4.08    | 1.92 | (1)(2)(3)(5)                      |
materials were indistinguishable from one another.

In the tooth composite model, the pulpal floor of the preparations of sound teeth were lined (Figs. 4a, d) with the base material of calcium hydroxide (Dycal) and a resin modified glass ionomer (RMGI) and Vitrebond. For the demineralized samples, residual dental demineralized soft tooth structure was intentional left (Fig. 4g). CP-OCT images of the two base materials and soft dentin are presented (Fig. 4) before and after the resin composite was placed. Analysis of the mR before and after the composite resin was placed (Table 2) measures how the resin composite attenuates the backscattering of the base materials and dentinal demineralization. The calcium hydroxide base (Dycal) had a higher scattering than dentinal demineralization and Vitrebond before and after the resin restoration was placed (ANOVA; p<0.001; Tukey-Kramer, p<0.05). Under the restoration, the dental demineralization and Vitrebond placed tooth samples were indistinguishable based on their backscattering properties. Since CP-OCT is able to measure depth precisely, a quality assurance evaluation revealed that although the dentist prepping the teeth had manually measured the depth of the preparation at 2.5 mm, the axial depth distances were not equal between the three groups and that the manual measurements that the dentists made had an error of ~1 mm. To address this error, a plot of the mR versus the depth of the calcium hydroxide (Dycal) allowed for a linear regression analysis. With a high coefficient of determination (R²=0.84), the regression equation (y=29.65+5.43x) allowed the mR value of the calcium hydroxide Dycal to be estimated at the average depth of the dentinal demineralization samples. The mR signal of the Dycal calcium hydroxide would be lowered from 13.86 dB to 9.28 dB with this linear regression depth correction, and this corrected value was still markedly higher than the dentinal caries measured (1.51 dB). This linear regression also shows how the mR signal varies significantly depending on the depth under the composite restoration.

### DISCUSSION

Secondary caries remains the main reason for composite restoration failure and has been shown to be nearly 3.5 times higher than amalgam failure. Clinicians routinely use protective bases to address several issues for patients, which includes management of sensitivity and extensive dental caries. Clinicians have no clear choice for an ideal protective liner/base based on a lack of strong clinical trials and evidence. This creates non-standard practices of using a variety of materials as liners for the management of dental caries. It is fortunate that calcium hydroxide is not used as ubiquitously as GI/RMGI under composite/resin restorations. But calcium hydroxide is still often used as a liner under permanent tooth restorations and is also commonly used as an indirect pulp capping for restorations in primary teeth in children.

The general list of possible materials used for base liner materials include the materials studied in this paper: glass ionomers, resin modified glass ionomers, and calcium hydroxide based materials.

If OCT/CP-OCT does become adopted into dental practice, careful selection of base material will be needed. For CP-OCT imaging analysis, the real world problem that clinicians are using a variety of base materials makes identifying dental caries under composite restorations incredibly challenging. In addition, residual amounts of base materials can be inadvertently placed and left on inner enamel walls during placement. The challenge in the United States will be substantial since patients migrate to different offices depending on insurance type and availability. Dentists often do not have current and full dental history records of a patient, since there are numerous different patient electronic health record systems and patients have to actively consent to patient record transfer. The results of this uncoordinated ecosystem of dental offices is problematic for CP-OCT evaluation. A dentist examining a new patient’s tooth with a previously placed resin composite restoration from another office may not know the previous history of the restorative procedure of the tooth. In some cases, records may be retrieved from another office or long term in-office patients of record can be properly screened. But even in these cases, the extent of the base/liner placement within the cavity preparation is difficult to document.

This current study demonstrates that calcium hydroxide based materials have scattering properties that are greater than both natural dentinal demineralization and the enamel caries phantom of compressed hydroxyapatite. For this study, compressed HA was a highly reproducible caries phantom (as evident from the small 95% confidence intervals), and it allows for cross comparison to other materials as shown in our previous work. Calcium hydroxide’s high scattering is likely the result of a similar structure as our caries phantom where the compressed powder creates a high number of grain boundaries with refractive index mismatch between particles and air. Dycal also contains both zinc and titanium oxide which are specific radio-opacifiers that have been shown to also highly scatter infrared light.

From these results, the Dycal base material could confound secondary caries diagnosis for dentists due to the high scattering properties of the material. It is important to consider that dentists are traditionally trained to assess X-ray imaging. When assessing X-rays, a dentist assesses a gradient of mineral densities in the form of grayscale values in an image. Most dental materials, like bases and resin composites, have added radio-opacifiers to prevent these materials from looking too similar to low density carious tissue. Depending on the radio-opacifier chosen, the material can also have high optical scattering in the near infrared but this depends on the localized refractive index of the resin and filler components. In the case of CP-OCT, sound tissue has lower scattering than carious tissue, and Dycal produced a high scattering effect like demineralization. This poses a significant problem to dentist trained in...
assessing a gradient of signals where one side of the gradient represents normal tissues (sound tissue and restorative material) and the other side of the gradient represents disease or defects (carious lesions or air gap spaces). In the case of having Dycal base materials in CP-OCT imaging, these bases are shown to scatter at levels that may be too close to demineralized enamel and dentin.

It is theoretically possible that a Dycal calcium hydroxide could be differentiated from demineralization based on its statistically significant higher scattering properties. While this could be done in well controlled studies, there are several potential problems with this potential in clinical practice. This present study used a depth correction approach by utilizing a Beer-Lambert plot of depth and scattering. The signal of Dycal calcium hydroxide could be estimated at different depths based on the linear regression approach. But previous studies have shown that the attenuate coefficients of the resin composite itself (which in this study was consistently the same) also vary greatly. The attenuation of resin materials depend on various composition differences. In order to identify calcium hydroxide’s higher scattering feature from enamel/dentinal demineralization, the dentist would need to know the type of resin dental composite that was placed. If the dentist had knowledge of this composite and the attenuation coefficient of the resin composite was available, the dentist (with the assistance of a computer program) could estimate if the scattering property of the structure under the composite was similar to calcium hydroxide. But knowledge of the type of resin dental composite also requires previous information and records of the patient. This returns to a practical issue in obtaining previous records. Without such previous record, it is unlikely that a dentist can assess the type of composite by visual examination alone. This highlights the complexity of having a material structure that scatters at a higher level than demineralized tissue. This study classified dentin demineralization based on tactile criteria, and future studies should further examine the optical properties of demineralized dentin using caries indicator dyes that can further differentiate infected from affected dentin.

There was a limitation in further investigating Dycal due to its poor physical properties. We were unable to section and analyze the samples under different microscopy techniques without the presence of a damaged interfacial boundary. Another research group has shown that artificial defects and artifacts can be created when using a precise sectioning saw on calcium hydroxide materials. Another limitation is that the present study used a disc model with precise geometric design, and the results of the study may not translate to analysis of non-uniform cavity designs.

There are newer materials that are also gaining popularity as protective base/liner materials in the dental marketplace. These include light-cured, resin-modified calcium silicate and mineral trioxide aggregate (MTA). While this study did not directly test these newer materials, the existence of these materials reinforces the complexity of real world CP-OCT secondary caries assessment since there is a range of materials that can be used under resin composites. This alone complicates the potential benefit of using CP-OCT for the assessment of the presence of demineralization under the margin of resin composite restorations. Dentists who do adopted advanced imaging methods like OCT/CP-OCT will have to standardize their practice of using adhesive/composites in their purest form without the addition of specific high scattering bases.

While the results of this study identifies calcium hydroxide base materials having a high scattering property that can be potentially misinterpreted as secondary caries, controlled clinical scenarios may utilize CP-OCT imaging for assessing underlying conditions. In these controlled clinic situations, knowledge of the type of dental composite and the presence of a base material will assist dentists in determining the presence of underlying dental demineralization.

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CONFLICT OF INTEREST

The authors of this manuscript certify that they have no proprietary, financial, or other personal interest of any nature in any product, service, and company that is presented in this article.

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