Light-Cured Self-Etch Adhesives Undergo Hydroxyapatite-Triggered Self-Cure

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Abstract

Light cure is a popular mode of curing for dental adhesives. However, it suffers from inadequate light delivery when the restoration site is less accessible, in which case a self-cure mechanism is desirable to salvage any compromised polymerization. We previously reported a novel self-cure system mediated by ethyl 4-(dimethylamino)-benzoate (4E) and hydroxyapatite (HAp). The present work aims to investigate if such self-cure phenomenon takes place in adhesives that underwent prior inadequate light cure and to elucidate if HAp released from the dental etching process is sufficient to trigger it. Model self-etch adhesives were formulated with various components, including bis[2-methacryloyloxyethyl]-phosphate (2MP) as acidic monomer and trimethylbenzoyl-diphenylphosphine oxide (TPO) as photoinitiator. In vitro evolution of degree of conversion (DC) of HAp-incorporated adhesives was monitored by infrared spectroscopy during light irradiation and dark storage. Selected adhesives were allowed to etch and extract HAp from enamel, light-cured in situ, and stored in the dark, after which Raman line mapping was used to obtain spatially resolved DC across the enamel-resin interface. Results showed that TPO+4E adhesives reached DC similar to TPO-only counterparts upon completion of light irradiation but underwent another round of initiation that boosted DC to ~100% regardless of HAp level or prior light exposure. When applied to enamel, TPO-only adhesives had ~80% DC in resin, which gradually descended to ~50% in enamel, whereas TPO+4E adhesives consistently scored ~80% DC across the enamel-resin interface. These observations suggest that polymerization of adhesives that underwent insufficient light cure is salvaged by the novel self-cure mechanism, and such salvaging effect can be triggered by HAp released from dental substrate during the etching process.

Keywords: chemical-curing of dental adhesives, ethyl 4-dimethylaminobenzoate, light-curing of dental adhesives, (2,4,6-trimethylbenzoyl) diphenylphosphine oxide, Fourier transform infrared spectroscopy, Raman spectroscopy

Introduction

Contemporary dental adhesives are predominantly based on acrylic resins, which cure via free radical polymerization (Van Landuyt et al. 2007). Free radicals are commonly generated by photoinitiation with a light-cure unit. The advantages for dentists are full control of the beginning of restoration and therefore unlimited work time. However, the convenience of light cure is accompanied by the risk of compromised light delivery when the restoration site is less accessible, for instance, in posterior teeth, deep cavity, and endodontic preparations (Shortall et al. 2002). Inadequate light cure leads to poor polymerization, which can cause myriad problems, including reduced bond strength, microleakage, toxicity, and postoperative sensitivity (Baek et al. 2008; Goldberg 2008; Federlin and Price 2013; Leprince et al. 2013). Alternatively, dentists can use dual-cure adhesives, which self-cure in the absence of light with additional chemical initiators such as organic peroxide and aryl sulfinate salt (Kwon et al. 2012). However, the radical generation in current chemical initiation systems is completely spontaneous and thus uncontrollable. Consequently, adhesive and chemical activator must be stored separately out of storage stability considerations, and technique complexity arises as the 2 components must be thoroughly mixed on site. More important, once the 2 components are mixed, there is only a small

window for dentists to apply the adhesive before it prematurely sets. In fact, the work time of most dual-cure adhesives is only a few minutes, not nearly as user-friendly as light-cure adhesives highlighting unlimited work time.

One countermeasure to uncontrolled self-cure is chemical initiation systems whose constituents include a compound originated from teeth. This way, the self-cure mode remains dormant until adhesive is applied to tooth and acquires the missing ingredient. Pertaining to this rationale, we previously reported that an aryl tertiary amine, ethyl 4-dimethylaminobenzoate (4E), triggered the polymerization of a model self-etch adhesive (SEA) containing bis[2-(methacryloyloxy)ethyl] phosphate (2MP) at room temperature upon the addition of bases such as hydroxyapatite (HAp) (Zhang and Wang 2012; Bai et al. 2013). Reaction of a similar nature (i.e., radical polymerization initiated by the amine-acid complex [RPAAC]) has been described, but none has reported the necessity of a

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base trigger (Lal and Green 1955; Uehara 1958, 1960; Sato et al. 1981; Antonucci et al. 1992; Farahani et al. 1997; Schumacher et al. 1997; Kotal et al. 2010). Since HAp is ubiquitously found in dentin and enamel, the base-triggered radical polymerization via the amine-acid complex (BT-RPAAC) is a great candidate for user-controlled self-cure.

Building on these discoveries, the present work aims to investigate whether BT-RPAAC can improve the polymerization of SEAs that underwent prior inadequate light cure. It is the very situation in which we would want chemical initiation to kick in and salvage any compromised polymerization. We evaluated model SEAs at various dosages of HAp and light irradiation for degree of conversion (DC) and flexural modulus (E_f). Then we applied the adhesives to tooth in a clinic-mimicking fashion and inspected whether the HAp released from the etching process was sufficient to trigger RPAAC. The tested null hypothesis was that BT-RPAAC would not occur under either circumstance.

Materials and Methods

Formulation of Model Adhesives

2-Hydroxyethyl methacrylate (HEMA), bis[2-(methacryloyloxy)ethyl] phosphate (2MP), hydroxyapatite (HAp), ethyl 4-dimethylaminobenzoate (4E), and trimethylbenzoyl-diphenylphosphine oxide (TPO) were purchased from Sigma-Aldrich (St. Louis, MO, USA). The formulation of model light-cure (TPO-only) and dual-cure (TPO+4E) SEAs started with the preparation of 2MP/HEMA neat resin at a 50/50 weight ratio, followed by the addition of TPO (0.022 mmol/g neat resin, or 0.77 wt%) to both adhesives and extra 4E (0.088 mmol/g neat resin, or 1.7 wt%) to the latter. Deuterium oxide (Cambridge Isotope Laboratories, Andover, MA, USA) or deionized water was added at 20 wt% with respect to neat resin to finalize the formulations.

Degree of Conversion (DC)

Polymerization of adhesives was monitored in real time using a Fourier-transformed infrared (FTIR) spectrometer equipped with an attenuated total reflectance (ATR) attachment (Spectrum One; Perkin-Elmer, Waltham, MA, USA) at a resolution of 4 cm^{-1} . The ATR crystal was diamond with a transmission range between 650 and $4,000\text{ cm}^{-1}$. HAp (2, 4 and 6 wt% with respect to adhesive) was individually added to the deuterated adhesives. Deuteration removes water's interference to FTIR peaks between $1,800$ and $1,500\text{ cm}^{-1}$, a crucial range for the determination of DC (below). Each HAp-containing adhesive was vortexed for 1 min to facilitate the dissolution of HAp, and then a small drop was placed on the ATR top plate, which was subsequently covered by a plastic cover slip (Fisher Scientific, Pittsburgh, PA, USA). Automatic acquisition of spectra started immediately after, using TimeBase software (Perkin-Elmer). Each run comprised 2 phases. In the initial light-cure phase, continuous spectra collection was performed with 0.4- to 0.6-s spectra acquisition intervals depending on acquisition speed.

After collecting the initial ~50 spectra for adhesive at the uncured state, light irradiation commenced and lasted for 10, 15, or 20 s. Conventional dental light (Spectrum Light; Dentsply, Milford, DE, USA) was used with output power at 600 mW/cm^2 , and the curing tip was purposely placed at a long distance (2.5 cm) away from the cover slip. The light-cure phase extended beyond light irradiation for a total of 5 min. In the following dark storage phase, spectra collection continued for 16 h, and the time interval between acquisitions was fixed at 10 min.

DC was assessed based on a band ratio between $1,637\text{ cm}^{-1}$ (methacrylate C=C stretching) and $1,454\text{ cm}^{-1}$ (CH_2/CH_3 scissoring). A 2-point baseline correction and maximum height protocol was employed to measure band intensities. For each adhesive, the initial band ratio (i.e., uncured state) was determined by averaging the values obtained from the first 30 spectra. DC was calculated by the following equation:

$$\text{DC} = \left(1 - \frac{\text{Absorbance}_{1,637\text{ cm}^{-1}}^{\text{Cured}} / \text{Absorbance}_{1,454\text{ cm}^{-1}}^{\text{Cured}}}{\text{Absorbance}_{1,637\text{ cm}^{-1}}^{\text{Uncured}} / \text{Absorbance}_{1,454\text{ cm}^{-1}}^{\text{Uncured}}} \right) \times 100\%.$$

Flexural Modulus (E_f)

TPO-only and TPO+4E adhesives were injected into Teflon molds ($15\text{ mm} \times 4\text{ mm} \times 1.1\text{ mm}$) immediately after incorporation of 4% HAp. They were light-cured at a distance of 2.5 cm for 10, 15, or 20 s while being covered by plastic cover slips. A total of 60 specimens were prepared ($n = 5$), which were stored in dark, sealed containers for 5 min or 24 h before being removed from the molds and tested on a Deben microtester (Deben UK Ltd., Suffolk, UK) with a 3-point bending setup. The crosshead speed was 1.0 mm/min . From the collected force-displacement curve, E_f was determined using the following equation:

$$E_f = \frac{L^3 m}{4bd^3},$$

where L is support span (10 mm), b is width of the specimen (4 mm), d is thickness of the specimen (1.1 mm), and m is the slope of the initial straight-line portion of the force-displacement curve (N/mm).

Experiments In Situ

Twelve noncarious third molars were collected from young adults with patients' informed consent under a protocol approved by University of Missouri–Kansas City Adult Health Sciences Institutional Review Board (IBC#12-14). Extracted teeth were stored at 4°C in 0.96% (w/v) phosphate-buffered saline containing 0.002% sodium azide. Preparation of enamel specimens was according to Figure 1. Raman line mapping was performed under a $100\times$ lens of a LabRam HR800 Raman spectrometer (Horiba Jobin Yvon, Edison, NJ, USA) with a monochromatic He-Ne laser (632.8 nm). The scan line was centered at the enamel-resin interface and perpendicularly

Figure 1. Schematic illustration of the preparation of enamel specimens. Using a water-cooled low-speed diamond saw (Buehler, Lake Bluff, IL, USA), the occlusal crown of each tooth was obtained, and a small incision (approximately 1 mm deep) was made at the apex of crown in the occlusal-apical direction. For the purpose of subsequent fracturing, each piece of enamel was notched from the side opposite to the incision, at the mid-position and in the direction perpendicular to the long side of incision. The 12 pieces of enamel were pooled and randomly divided into 2 groups ($n = 6$). Using fine-tipped pipettes, trimethylbenzoyl-diphenylphosphine oxide (TPO) only or TPO+4E adhesive was injected into the incision. After etching for 1 min with the self-etch adhesive (SEA), the adhesive was light-cured for 10 s with the same dental light used in the attenuated total reflectance (ATR)–Fourier-transformed infrared (FTIR) experiments at 600 mW/cm² output power. The distance between curing tip and crown apex was 2 cm. The light-cured specimen was then stored in a dark, sealed environment at room temperature for 3 d. Following dark storage, the specimen was fractured, and the fractured surface was surveyed with Raman line mapping.

extended 10 μ m into the enamel and resin at 1- μ m intervals. Thus, 1 scan comprised 21 Raman spectra, each of which was collected over a spectral range of 700 to 1,800 cm^{-1} and with a 60-s acquisition time. With prior acquisition of Raman spectra from uncured adhesives, DC at each surveyed spot was calculated by the same method using the same 2 bands as the ATR-FTIR experiments.

Statistical Analysis

Statistical analysis was performed with SPSS 21.0 (SPSS, Inc., an IBM Company, Chicago, IL, USA) and nominal level of significance at 0.05. The normality of distribution and homogeneity of variances were confirmed with Shapiro-Wilk and Levene tests, respectively. For E_p , 3-way analysis of variance (ANOVA) was used to determine the interaction between independent factors, and comparison of means was done by split-file t test or 1-way ANOVA with Tukey's or Dunnett's T3 post

hoc analysis depending on whether homogeneity of variances was confirmed with Levene's test. For DC in situ, comparison of means was done with 1-way ANOVA and Tukey's post hoc test.

Results

All adhesives were colorless. The light-cure (TPO-only) adhesive had a pH of 0.15, which rose to 0.92 upon addition of 4% HAp. The dual-cure (TPO+4E) adhesive had a pH of 0.32 due to basic amine 4E. Upon addition of 2%, 4%, and 6% HAp, its pH elevated to 0.63, 1.00, and 1.20, respectively. Shown in Figure 2A, B are representative FTIR spectra of both adhesives. When uncured, almost identical spectra were seen, except that the TPO+4E one had a small shoulder (1,607 cm^{-1}) for aromatic C = C stretching (Liu and Wang 2013) attributed to 4E's phenyl rings. This shoulder was not visible in TPO-only adhesives despite TPO bearing phenyl rings as well, probably due to low TPO concentration. Light cure caused a substantial reduction to all bands related to methacrylate monomers, including aliphatic C = C stretching (1,637 cm^{-1}) and vinyl CH₂ wagging (815 cm^{-1}) (Figueiredo et al. 2013). The double peaks for ester C-O stretching (1,320 and 1,300 cm^{-1}) shrank due to loss of conjugation from methacrylate double bonds (Young et al. 2004). Light cure also caused the emergence of a new band at 747 cm^{-1} , corresponding to

the rocking motion of a special group of CH₂ only found in polymerized methacrylates (Figueiredo et al. 2013), that is, the saturated CH₂ sandwiched between 2 tertiary carbons each bearing 1 methyl group and 1 methyl ester (–COOCH₃) group. During dark storage, spectra of the TPO-only formulation did not undergo any further changes. In contrast, bands at 1,637, 1,320, 1,300, and 815 cm^{-1} almost vanished in TPO+4E formulations, and the band at 747 cm^{-1} grew more prominent.

Time-resolved DC curves of adhesives at fixed HAp content (4 wt% HAp) but various light exposures are shown in Figure 3A–C. At each light exposure, adhesives with and without 4E exhibited analogous sigmoid-shaped curves in the light-cure phase with DC ending at ~25%, ~50%, and ~75% for light exposure of 10, 15, and 20 s, respectively. Such resemblance ceased to exist in the dark storage phase. Flat lines were recorded throughout this period for TPO-only adhesives, whereas for TPO+4E adhesives, flat lines were only seen at the beginning of dark storage, which later climbed to almost 100%,

generating another sigmoidal trace. The same phenomenon was observed when the light exposure was fixed (15 s) but HAp concentration was different (Fig. 3D).

Regarding E_f , 3-way ANOVA revealed that interaction between initiator, light-cure time, and dark storage is significant ($P < 0.05$), and therefore split file comparison was performed. For TPO-only adhesives (Fig. 4A), longer light exposure resulted in significantly higher E_f immediately after light cure (1.0 ± 1.7 , 48.9 ± 20.9 , and 190.8 ± 38.7 MPa for 10-, 15-, and 20-s light cure, respectively). After dark storage, the E_f values did not change, arriving at 0.4 ± 1.5 , 46.7 ± 22.3 , and 191.7 ± 26.0 MPa, respectively. In contrast, dark storage significantly increased E_f for TPO+4E adhesives (Fig. 4B), from 0.4 ± 1.6 to 242.5 ± 44.6 MPa for a 10-s light cure, from 87.6 ± 8.4 to 222.8 ± 21.7 MPa for a 15-s light cure, and from 168.1 ± 8.4 to 203.9 ± 14.8 MPa for a 20-s light cure. In addition, the flexural modulus of all TPO+4E resins became statistically equivalent after dark storage.

A representative optical image of the fractured surface of an enamel specimen is shown in Figure 5A. Typical spectra collected along scanned lines are demonstrated in Figure 5B, C together with those of pure enamel and uncured adhesives. Similar to FTIR measurement, the 2 adhesives had almost identical Raman spectra at the uncured state, except for the additional shoulder at $1,607\text{ cm}^{-1}$ owing to 4E in TPO+4E adhesives. After etching, light curing, and dark storage, SEAs apparently penetrated into enamel as evidenced by the characteristic resin bands on the enamel side of resin-enamel interface. Spectra collected from resin-infiltrated enamel showed intensified signals at 997, 1,590, and $1,607\text{ cm}^{-1}$, but this phenomenon was not observed in resin (Fig. 5B, C, shaded areas). The spatially resolved DCs of TPO-only and TPO+4E adhesives on enamel are shown in Figure 5D. Both adhesives exhibited steady and similar DC ($\sim 80\%$) in the resin layer. However, DC of the former started to decrease from the enamel-resin interface toward enamel. Significantly lower DC was recorded at $3\text{ }\mu\text{m}$ from the interface, which further decreased to $\sim 50\%$ at 8 to $10\text{ }\mu\text{m}$ in enamel. In contrast, DC of the latter adhesive did not change in enamel.

Discussion

Reports of vinyl polymerization initiated by amine and acid can be traced back to the 1950s (Lal and Green 1955). Despite the long span of publication (Uehara 1958, 1960; Kotal et al. 2010; Sato et al. 1981), this initiation did not garner much attention in the dental field. To our knowledge, only in the 1990s were there investigations of carboxyl-bearing secondary/ tertiary

Figure 2. Representative Fourier-transformed infrared (FTIR) spectra of (A) trimethylbenzoyl-diphenylphosphine oxide (TPO)-only and (B) TPO+4E adhesives at the uncured state, after light cure, and after dark storage. The particular formulations contained 4 wt% hydroxyapatite (HAp). All spectra were normalized against the band of CH_2/CH_3 scissoring at $1,454\text{ cm}^{-1}$.

amines (e.g., N-phenylglycine, N-phenyliminodiacetic acid) in dentin bonding (Antonucci et al. 1992; Farahani et al. 1997; Schumacher et al. 1997). However, these amines share the same drawback of regular chemical initiators in spontaneity possibly due to the coexistence of acid and amine on the same molecule so that the acid-amine balance is always maintained (Bai et al. 2013). In comparison, the system under our examination has far more acid (2MP) than amine (4E), which necessitates additional base (HAp), resulting in user-controlled initiation.

The sigmoidal DC curves in the light-cure phase (Fig. 3) are typical for photoinitiated polymerization (Guo et al. 2008; Ye et al. 2009; Liu and Wang 2013). The close resemblance in plateau DC regardless of 4E's presence (Fig. 3A–C) or HAp content (Fig. 3D) is consistent with the notions that TPO's photoinitiation is not interfered by 4E (Baxter et al. 1988) or pH (Wu et al. 2013). These 2 characteristics are the reasons we chose TPO as the photoinitiator as opposed to the widely used 2-component and 3-component systems based on camphorquinone (CQ), amine, and optional iodonium salt. Indeed, the chemical initiation under investigation involves a tertiary amine (4E), which reacts with light-activated CQ to generate free radicals (Santini et al. 2013). Therefore, using CQ/amine photoinitiators would obscure the role of 4E as a light-cure and self-cure initiator. Moreover, many studies have reported the incompatibility of CQ/amine systems with acidity, presumably due to amines turning into the protonated form in an acidic environment (Tay et al. 2003; Moszner et al. 2005; Zhang and

Figure 3. Degree of conversion (DC) curves of (A–C) trimethylbenzoyl-diphenylphosphine oxide (TPO)-only and TPO+4E adhesives that contained the same amount of hydroxyapatite (HAp) (4 wt%) but were subject to different light exposure, and (D) TPO+4E adhesive that were subject to the same light exposure (15 s) but contained a different amount of HAp.

Wang 2012). Therefore, using pH-independent TPO would eliminate the interference of pH both in the FTIR analysis where a different amount of HAp is added and in the subsequent spatially resolved DC determination where an acidity gradient is inevitably produced when the adhesive is applied on enamel.

Concerning the dark storage phase (Fig. 3), the DC change of TPO-only adhesives serves as a baseline for any postcure dark polymerization resulting from residual photogenerated living radicals trapped in resin matrix (Leung et al. 1983; Anseth et al. 1996; Lecamp et al. 1999; Pavlinec and Moszner 2003). The flat lines of TPO-only adhesives indicate that no obvious dark polymerization took place, possibly due to low viscosity of the resins with high water content. In contrast, TPO+4E adhesives featured sigmoid-shaped DC curves in dark storage, which strongly suggests an additional round of initiation. The stages of induction, auto-acceleration, and finishing were consistent with our previously reported BT-RPAAC in adhesives without light cure (Zhang and Wang 2012; Bai et al. 2013). At fixed HAp level (4%), the auto-acceleration of BT-RPAAC was reached sooner for adhesives with higher light cure-induced DC (hence higher viscosity). The trend is anticipated because auto-acceleration occurs when the rate of initiation surpasses termination. At higher viscosity, the polymeric species involving termination is retarded, whereas monomer-involving initiation is less affected, leading to faster auto-acceleration. At fixed light exposure (15 s), the adhesives at a higher HAp level arrived at the auto-acceleration stage sooner, consistent with our previous findings that higher HAp content facilitated initiation of the 2MP-4E acid-amine pair (Zhang and Wang 2012; Bai et al. 2013). Clearly, the null hypothesis that BT-RPAAC does not occur in inadequately light-cured adhesives has to be rejected *in vitro*.

The mechanical characterization of cured adhesives strongly corroborates DC determination (Fig. 4). Elongation of light exposure significantly increased E_f immediately after light curing, consistent with the DC values determined (~25%, ~50%, and ~75% for 10-s, 15-s, and 20-s exposure, respectively, as seen in Fig. 3). For TPO-only adhesives, the equivalent E_f before and after dark storage (Fig. 4A) is in agreement with the observation that no dark polymerization occurred (Fig. 3A–C). In contrast, dark storage significantly elevated the E_f of TPO+4E adhesives to a light

exposure-independent level (Fig. 4B), further verifying that BT-RPAAC was active in light-cured adhesives, which continued to boost monomer conversion to near 100% (Fig. 3A–C).

In clinical situations, SEAs become incorporated with HAP when they etch dentin and enamel. To examine if BT-RPAAC is activated by HAP from such dental sources, we chose enamel rather than dentin to be the etching substrate because dentin collagen's amide I band in Raman spectroscopy (Wang and Spencer 2005) overlaps with the aliphatic C = C stretching band ($1,637\text{ cm}^{-1}$). Spectrum subtraction could theoretically erase this interference, but artifacts have been noted in such a practice (Aparicio et al. 2002). Using enamel circumvented the issue (Fig. 5) and rendered accurate and quick determination of DC. The band at 997 cm^{-1} is characteristic for bending deformation and those at $1,590$ and $1,607\text{ cm}^{-1}$ for stretching vibration of benzene rings (Fig. 5B, C) (Schrader 1995). Enhancement of these bands in enamel could be due to delocalized π -electrons of TPO/4E benzene rings as a result of increased cation (Ca^{2+})– π interaction (Kumpf and Dougherty 1993) in a HAP-rich environment. The DC change of TPO-only adhesive across the enamel-resin interface (Fig. 5D) is consistent with the light irradiation each zone received. That is, the direction of light was parallel to the interface, so along the mapping lines, areas within the prepared incision were subject to equivalent irradiation and consequently reached equivalent DC, whereas areas deeper in the enamel received gradually reduced irradiation and therefore gradually reduced DC. In comparison, there was no DC change across the enamel-resin interface for TPO+4E adhesives, which indicates that in areas that suffer from inadequate light cure, BT-RPAAC kicked in and salvaged polymerization. Thus, the null hypothesis that BT-RPAAC does not occur with HAP originating from a clinical etching process is rejected.

Although TPO was the photoinitiator of choice in the present study, it is reasonable to believe that BT-RPAAC occurs in SEAs with CQ/amine photoinitiation systems, too, as long as the amine is capable of BT-RPAAC and not completely consumed by photoinitiation. We may have unknowingly taken advantage of some amines' BT-RPAAC capability in current SEA formulations but likely not to the full extent due to the lack of knowledge about it. Notably, RPAAC was found to be a quasi-living system (Kotal et al. 2010), which is corroborated by the near 100% DC reported previously (Zhang and Wang 2012; Bai et al. 2013) and currently

Figure 4. Flexural modulus of (A) trimethylbenzoyl-diphenylphosphine oxide (TPO)-only adhesives and (B) TPO+4E adhesives incorporated with 4% hydroxyapatite (HAP); light-cured for 10, 15, and 20 s; and then selectively stored in dark for 24 h. Star (*) indicates significant difference between adhesives with the same initiator and light exposure but different storage. Different lowercase letters indicate significantly different flexural modulus for adhesives with the same initiator but different light exposure before dark storage. Different uppercase letters indicate significantly different flexural modulus for adhesives with the same initiator but different light exposure after dark storage.

(Fig. 3). However, only about 80% DC was recorded on enamel (Fig. 5D), possibly a ramification of the experimental formulations' ineptitude to extract the right amount of HAP during the etching process. Hence, further studies are needed to maximize the effect of BT-RPAAC in dental adhesion, which should cover various acidic monomers and tertiary amines at different concentrations.

To summarize, we verified that chemical initiation mediated by the acid-amine pair of 2MP-4E can salvage compromised polymerization caused by inadequate photoinitiation. The discovery should serve as a stepping stone toward the mostly uncharted area of BT-RPAAC-related self-cure in dental adhesives.

Author Contributions

Y. Liu, contributed to conception, design, data acquisition, analysis, and interpretation, drafted and critically revised the manuscript; X. Bai, contributed to data acquisition and analysis, critically

Figure 5. Raman line mapping of enamel-resin interface. **(A)** Representative optical image of the enamel-resin interface to be surveyed with Raman line mapping. Area of interest is highlighted by the red line. **(B, C)** Representative Raman spectra sampled from different spots of line mapping in enamel restored with **(B)** trimethylbenzoyl-diphenylphosphine oxide (TPO)-only adhesive and **(C)** TPO+4E adhesive together with spectra of uncured adhesive and pure enamel. The only bands seen in pure enamel were PO_4^{3-} v1 vibration (960 cm^{-1}) and v3 vibration ($1,044, 1,070\text{ cm}^{-1}$), which had no interference with the aliphatic C = C stretching band for degree of conversion (DC) determination. **(D)** DC of TPO-only and TPO+4E adhesives across the enamel-resin interface after light cure and dark storage ($n = 6$).

revised the manuscript; Y.W. Liu, contributed to data analysis and interpretation, critically revised the manuscript; Y. Wang, contributed to conception, design, data analysis, and interpretation, critically revised the manuscript. All authors gave final approval and agree to be accountable for all aspects of the work.

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