Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Analysis of Monomer Elution from Different Composite Materials in Clear Aligner Treatments Using High Performance Liquid Chromatography : In-Vitro Evaluation

Nihal Kaya
dt.nihalsimsek@gmail.com
Bezmiâlem Vakıf Üniversitesi
Şerife Şahin
Bezmiâlem Vakıf Üniversitesi
Alper Külçü
Bezmiâlem Vakıf Üniversitesi
Gizem Tırıs
Bezmiâlem Vakıf Üniversitesi

Research Article

Keywords: attachment, clear aligner, monomer elution

Posted Date: April 23rd, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9160597/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License

Additional Declarations: No competing interests reported.

Abstract

Background

This in vitro study evaluated monomer release from different light-cured composites used for clear aligner attachments over time, assessing the effects of composite type, attachment size and curing duration.

Methods

Four composite materials (3M™ Filtek™ Supreme Flowable, 3M™ Filtek™ Z350 XT Universal, 3M™ Transbond™ XT, and Tokuyama Estelite Posterior) were shaped into attachment-like specimens using 3D-printed molds with heights of 3 mm, 4 mm, and 5 mm. Polymerization was performed using a VALO LED curing unit with two curing protocols (6 s and 12 s). Monomer release was quantified at 1 hour, 1 day, 7 days, and 14 days using high-performance liquid chromatography (HPLC). Statistical analyses were performed using Kruskal–Wallis and post-hoc Bonferroni tests ($p < 0.05$).

Results

Intragroup analyses demonstrated significant height- and time-dependent differences in TEGDMA and Bis-GMA release for all composites under both curing protocols ($p < 0.001$). Under 6 s curing, monomer release increased with specimen height, whereas 12 s curing reduced early elution and yielded more stable profiles. Intergroup comparisons revealed significant differences among composites at all heights, curing durations, and time points (mostly $p < 0.001$).

Conclusion

Light-curing duration, attachment size, and composite type significantly influence monomer release.

INTRODUCTION

The increasing demand for aesthetic orthodontic treatment has led clinicians to embrace the use of clear aligners [1]. Clear aligner therapy provides multiple benefits compared to traditional fixed braces, such as better aesthetics, the ability to remove them, and increased comfort [2]. Clear aligner therapy often requires the use of attachments to enhance aligner retention and facilitate challenging orthodontic movements, thereby improving the effectiveness of orthodontic treatments [3]. They vary in shape, size and configuration, allowing for customized treatment [4]. The attachments are composed of composite materials. The composites are dental polymer resin-based materials, which are composed of organic matrix and inorganic fillers. The organic matrix is derived from organic bisphenol A (BPA)-based monomers, such as bis-GMA (bisphenol-A-glycidyl methacrylate) and its ethoxylated form Bis-EMA, Bis-DMA (bisphenol-A dimethacrylate). They also contain non-BPA-based monomers, such as TEGDMA (triethylene glycol dimethacrylate), UDMA (urethane dimethacrylate), DMA (N,N dimethylacetamide), and HEMA (hydroethyl) methacrylate) [5]. Dental resins are not inert in the oral environment when the polymerization of the organic matrix is incomplete and intraoral degradation occurs over time, the degradation of composite resin facilitates the elution of free unbound monomers into the surrounding oral environment, potentially posing biological risks [6]. The degree of polymerization is influenced by various factors, including the initiator, filler content, size, color, light intensity, and curing time [7]. Depending on the free unbound monomer threshold concentration levels, they can cause allergic reactions, toxic or other effects. [8, 9]. BPA-based monomers act as endocrine disruptors, which can impact several hormone receptors, leading to issues with the immune system, reproductive organs in both men and women, thyroid function, and gene expression. [10, 11]. Additionally, TEGDMA, the most commonly used co-monomer, inhibits cell growth and lowers glutathione levels, disrupting metabolism. It is also genotoxic and interacts with the DNA of mammalian cells [12, 13].

Various analytical techniques have been employed to quantify residual monomer release from resin-based composite materials. These methods include ultraviolet spectrophotometry, multiplex internal reflection spectroscopy (MIRS), differential thermal analysis, laser Raman spectroscopy, Fourier TBXTform infrared spectroscopy (FT-IR), and chromatographic methods such as gas chromatography-mass spectrometry (GC-MS), thin layer chromatography, electrospray ionization-mass spectrometry, column chromatography, liquid chromatography-mass spectrometry (LC-MS), and high-performance liquid chromatography (HPLC)[14, 15]. Among these, chromatographic methods, particularly HPLC, have been identified as the most effective for analyzing residual monomers released from resin-based composites. HPLC provides high resolution and precise control over the separation process, enabling the reliable identification of monomeric components dissolved in the mobile phase [15, 16].

The aim of this study is to determine the amount of monomer release at different time intervals under in-vitro conditions, resulting from the polymerization of light-curing composite materials. The null hypotheses of the study are as follows: (1) There is no significant difference in the monomer release between composite materials. (2) The amount of monomer released from composite materials is not affected by the curing time. (3) The amount of monomer released from composite materials will remain constant over time.

MATERIAL-METHOD

The study complied with the Declaration of Helsinki. This in-vitro experimental study aimed to evaluate the effects of composite type, attachment size, and curing duration on the release of Bis-GMA and TEGDMA monomers at four immersion intervals.

The experimental matrix included four composite materials, two curing durations (6 s and 12 s), three attachment sizes (3 mm, 4 mm, 5 mm), and four immersion periods (1 h, 1 day, 7 days, 14 days). Each subgroup included nine specimens, yielding a total of 288 samples.

The dimensions of rectangular attachments are 3, 4, or 5 mm in height, 2 mm in width, and 1 mm in depth [17].

Composite Materials

The following light-cured resin composites were evaluated in Table 1.

Table 1
Composite Materials Used in the Study and Their Characteristic

Material	Code	Manufacturer	Type
3M™ Filtek™ Supreme Flowable Restorative	FSF	3M ESPE, St. Paul, MN, USA	Flowable nanofilled composite
3M™ Filtek™ Z350 XT Universal Restorative	Z350	3M ESPE, St. Paul, MN, USA	Z350versal nanohybrid composite
3M™ Transbond™ XT Light Cure Adhesive	TBXT	3M Z350tek, Monrovia, CA, USA	Orthodontic adhesive
Tokuyama Estelite Posterior	TEP	Tokuyama Dental, TEPyo, Japan	Microhybrid restorative composite

All materials were handled in accordance with the manufacturers' instructions under standardized laboratory conditions (23 ± 2°C, 50 ± 5% relative humidity).

Specimen Preparation

Attachment-shaped specimens were fabricated using 3D-printed templates that replicated the geometric form of orthodontic attachments in three different heights (3 mm, 4 mm, and 5 mm). Each template cavity was lined with a 1 mm-thick transparent thermoplastic sheet (vacuum-formed aligner material), serving as a standard base.

The composite material was carefully injected into the 3D mold cavity placed over the 1 mm sheet, ensuring full adaptation without air voids. After the material was positioned, it was covered with a Mylar strip and polymerized according to the designated curing protocol. The specimens were then gently removed from the mold, checked for surface irregularities, and stored in light-proof containers at 37°C for 24 hours to allow post-polymerization completion.

Light-Curing Protocol

Polymerization was performed using an LED light-curing Z350t (VALO, Ultradent Products Inc., South Jordan, UT, USA) with a calibrated light intensity of 1200 mW/cm², verified with a radiometer before each session. The light tip was held perpendicular to the specimen at a distance of 1 mm. Two curing durations were applied: 6 seconds (short-curing protocol), 12 seconds (extended-curing protocol).

Storage and Elution Procedure

After curing, each specimen was placed in 2 mL of 75% ethanol/distilled water (v/v) in a sealed glass vial and incubated at 37°C. The elution medium was collected and replaced at 1 hour, 1 day, 7 days, and 14 days. All eluates were stored at 4°C until chromatographic analysis.

HPLC Analysis

Bisphenol-A glycerolate dimethacrylate (BIS-GMA) and triethylene glycol dimethacrylate (TEGDMA) monomers were used as standard substance. The analysis was conducted on HPLC (Shimadzu, Kyoto, Japan) device. Experiments were carried out Inertsil® ODS-3 column (250 mm x 4.6 mm diameter and particle size 5 µm). Mobile phase was acetonitrile: water (80:20 v/v) and flow rate was 1.0 mL/min. Detection waveheight adjust to 254.0 nm. Injection volume was 20.0 µL.

Prepared composites were waited in ethanol:water (75:25 v/v) solvent and stored at room temperature in the dark. The mixture of ethanol and water added to the samples was taken at the 1st, 7th and 30th days and at the 1st hour and filtered and given to the HPLC device. Calibration graphs were constructed in the range of 0.25–50 µg/mL). A chromatogram of the analysed monomers is illustrated in Fig. 1. Standard substances were bought Sigma-Aldrich, St. Louis, MO, USA.

Statistical Analysis

All statistical analyses were performed using SPSS Statistics software (IBM Corp., Armonk, NY, USA). Data normality was assessed using the Shapiro–Wilk test. Since the majority of variables did not follow a normal distribution, intergroup comparisons were conducted with the Kruskal–Wallis test. When significant differences were observed, pairwise Bonferroni-adjusted post-hoc tests were applied to identify subgroup differences. Descriptive data were presented as minimum, maximum, and median values. Statistical significance was set at $p < 0.05$.

RESULTS

Intragroup Comparison of TEGDMA and BISGMA Release from Different Composite Resins of Different Heights under 6 s and 12 s Curing

The intragroup comparison of TEGDMA and BISGMA release from different composite resins of varying Heights under 6-second and 12-second curing conditions is presented (Tables 2–3).

Table 2
Intragroup Comparison of TEGDMA Release from Different Composite Resins of Different Thicknesses under 6 s and 12 s Curing

Material	Time	3 mm	4 mm	5 mm	Kruskal-Wallis p-value	3–4 mm	3–5 mm	4–5 mm
6 s curing								
FSF	1 h	2.99–6.33 (4.64)	3.84–6.26 (4.82)	4.50–21.62 (8.36)	0.058	–	–	–
	1 day	3.09–4.61 (3.25)	4.45–7.23 (5.88)	4.75–5.75 (5.08)	< 0.001	0.004	0.001	NS
	7 days	2.44–3.64 (3.15)	2.62–3.14 (2.84)	3.13–3.77 (3.57)	0.001	NS	0.04	0.001
	14 days	0.40–0.83 (0.72)	0.44–0.74 (0.59)	0.70–0.96 (0.88)	< 0.001	NS	0.01	< 0.001
TBXT	1 h	0.36–0.64 (0.46)	0.41–0.88 (0.63)	0.77–1.00 (0.90)	0.02	NS	0.01	NS
	1 day	1.17–1.65 (1.27)	1.15–1.69 (1.35)	1.21–1.95 (1.55)	< 0.001	< 0.001	0.002	NS
	7 days	1.28–1.80 (1.56)	1.57–2.50 (2.03)	2.38–2.71 (2.54)	< 0.001	< 0.001	< 0.001	0.01
	14 days	0.24–0.47 (0.36)	0.53–0.73 (0.59)	0.52–1.10 (0.80)	0.003	NS	0.008	0.01
Z350	1 h	0.208–0.425 (0.262)	0.237–0.412 (0.273)	0.26–0.335 (0.295)	0.41	–	–	–
	7 days	0.595–0.892 (0.743)	0.957–1.122 (1.065)	0.968–1.329 (1.051)	< 0.001	0.009	0.004	NS
	14 days	0.14–0.225 (0.203)	0.281–0.343 (0.315)	0.228–0.419 (0.369)	< 0.001	0.001	0.003	0.01
TEP	1 h	4.86–50.78 (48.88)	33.76–74.72 (53.32)	55.83–107.89 (71.21)	< 0.001	0.04	0.009	0.04
	1 day	34.18–54.29 (50.2)	30.77–67.86 (60.91)	48.96–69.69 (58.7)	0.14	–	–	–
	7 days	15.07–20.25 (19.15)	11.27–22.73 (21.77)	11.96–25.73 (22.99)	0.16	–	–	–
	14 days	0.724–2.005 (1.091)	0.269–2.893 (0.749)	0.506–1.763 (0.827)	0.34	–	–	–
12 s curing								
FSF	1 h	1.13–2.88 (2.24)	1.41–3.01 (2.68)	1.45–2.71 (1.6)	0.42	–	–	–
	1 day	1.03–1.45 (1.25)	1.51–1.93 (1.73)	0.21–2.71 (1.45)	0.001	0.001	NS	0.01
	7 days	0.72–1.08 (0.81)	1.01–1.23 (1.09)	1.04–1.43 (1.26)	< 0.001	< 0.001	< 0.001	0.003
	14 days	0.17–0.83 (0.37)	0.18–0.71 (0.37)	0.21–0.85 (0.5)	0.33	–	–	–
TBXT	1 h	0.90–1.16 (1.04)	1.09–1.32 (1.26)	1.42–1.64 (1.53)	< 0.001	< 0.001	< 0.001	< 0.001
	1 day	0.62–1.36 (1.07)	1.27–1.94 (1.48)	1.27–2.19 (1.90)	< 0.001	< 0.001	< 0.001	0.04
	7 days	0.82–1.32 (1.10)	1.22–2.20 (1.61)	1.31–2.39 (2.05)	< 0.001	< 0.001	< 0.001	0.01
	14 days	0.40–0.75 (0.57)	0.46–1.02 (0.91)	0.70–1.27 (0.94)	0.001	0.01	0.005	0.04
Z350	1 h	0–0 (0)	0–0 (0)	0–0 (0)	NAN	–	–	–
	1 day	0.245–0.316 (0.26)	0.205–0.383 (0.327)	0.329–0.626 (0.402)	0.001	0.03	0.004	0.01
	7 days	0.473–0.656 (0.531)	0.486–0.759 (0.599)	2.855–4.156 (3.36)	< 0.001	< 0.001	< 0.001	< 0.001
	14 days	0.289–0.449 (0.405)	0.303–0.588 (0.398)	0.243–0.931 (0.638)	0.009	NS	0.01	0.04
TEP	1 h	4.79–10.07 (6.56)	6.13–21.39 (15.74)	10.28–33.65 (14.26)	0.001	0.02	0.01	NS
	1 day	6.17–6.73 (6.45)	6.8–17.6 (16.67)	8.66–28.13 (14.8)	< 0.001	0.006	0.01	NS
	7 days	4.32–5.65 (4.99)	5.06–13.72 (13.36)	5.28–24.22 (8.07)	0.002	0.008	0.03	NS
	14 days	2.00–2.43 (2.23)	2.24–5.59 (4.59)	2.36–10.62 (3.44)	0.002	0.01	0.03	NS

Notes: NS = not significant; – = not applicable; NAN = all values identical.

Table 3
Intragroup Comparison of BISGMA Release from Different Composite Resins of Different Thicknesses under 6 s and 12 s Curing

Material	Time	3 mm	4 mm	5 mm	Kruskal-Wallis p-value	3–4 mm	3–5 mm	4–5 mm
6 s curing								
FSF	1 h	11.45–22.21 (16.69)	15.11–23.19 (17.37)	16.55–76.1 (31.1)	0.01	NS	0.01	0.004
	1 day	17.81–26.71 (21.13)	26.11–46.4 (35.56)	26.68–34.32 (28.75)	< 0.001	< 0.001	0.001	NS
	7 days	28.54–37.41 (31.82)	29.55–34.47 (33.2)	34.14–38.22 (35.58)	< 0.001	0.004	< 0.001	< 0.001
	14 days	8.97–16.21 (15.5)	14.15–16.03 (15.04)	15.64–17.48 (16.96)	0.001	NS	0.01	0.004
TBXT	1 h	19.68–28.65 (21.28)	26–76.66 (27.93)	24.73–34.18 (29.4)	0.003	0.03	0.009	NS
	1 day	38.92–55.18 (52.27)	42.74–57.62 (49.21)	47.51–61.28 (51)	0.58	–	–	–
	7 days	52.15–58.54 (55.55)	52.98–77.22 (75.8)	70.13–81.48 (73.13)	0.002	0.01	0.006	NS
	14 days	24.84–28.57 (25.59)	26–36.19 (34.12)	32.7–40.92 (37.18)	< 0.001	NS	0.003	0.01
Z250	1 h	7.63–15.1 (11.14)	6.34–17.48 (8.33)	7.66–14.71 (10.95)	0.76	–	–	–
	1 day	11.57–22.65 (19.01)	12.11–19.46 (16.11)	13.39–15.94 (14.74)	0.05	–	–	–
	7 days	3.46–5.9 (5.05)	5.21–6.94 (5.85)	4.45–8.81 (6.35)	0.009	0.04	0.007	NS
	14 days	2.11–11.28 (8.91)	8.26–11.49 (10.59)	8.54–14.99 (11.27)	0.01	NS	0.01	0.03
TEP	1 h	40.62–95.37 (77.2)	44.43–119.22 (89.61)	96.38–179.66 (125.03)	< 0.001	0.04	0.009	0.01
	1 day	87.92–135.32 (129.06)	75.48–166.53 (156.42)	118.74–162.77 (138.27)	0.19	–	–	–
	7 days	67.42–95.02 (75.42)	75.96–88.68 (84.69)	93.09–124.74 (96.02)	< 0.001	0.03	0.009	0.02
	14 days	23.74–27.46 (26.42)	17.06–29.61 (27.18)	14.01–318.58 (32.12)	0.34	–	–	–
12 s curing								
FSF	1 h	5.52–14.43 (10.18)	6.46–12.19 (10.68)	6.56–11.72 (6.74)	0.88	–	–	–
	1 day	7.07–13.49 (9.56)	8.65–11.44 (10.04)	8.25–11.17 (10.19)	0.95	–	–	–
	7 days	10.72–12.73 (12.05)	11.91–13.34 (13.07)	12.34–16.11 (15.36)	< 0.001	0.04	0.003	NS
	14 days	8.33–11.12 (10.04)	9.92–11.69 (10.58)	10.26–12.3 (11.88)	0.003	NS	0.01	NS
TBXT	1 h	55.93–71.01 (65.88)	61.26–90.46 (66.8)	71.27–94.45 (91.88)	< 0.001	0.03	0.006	0.01
	1 day	62.02–85.78 (77.99)	84.1–122.44 (117.16)	98.37–127.28 (123.81)	< 0.001	0.004	0.002	NS
	7 days	62.4–90.78 (82.66)	92.75–145.45 (116.41)	104.07–150.65 (140.57)	< 0.001	0.008	0.002	0.03
	14 days	35.38–52.4 (48.62)	59.88–89.94 (74.83)	68.01–95.49 (90.8)	< 0.001	0.02	0.002	0.01
Z350	1 h	0.47–1.809 (1.261)	0.825–2.505 (1.421)	7.664–14.711 (10.95)	< 0.001	NS	0.009	0.01
	1 day	0.773–1.221 (1.069)	1.918–3.046 (2.522)	2.855–4.156 (3.36)	< 0.001	0.001	< 0.001	0.002
	7 days	1.945–3.225 (2.526)	1.918–3.046 (2.522)	2.855–4.156 (3.36)	< 0.001	0.04	0.007	0.02
	14 days	0.973–2.662 (2.409)	2.081–2.913 (2.41)	2.484–3.532 (3.028)	0.001	NS	0.01	0.02
TEP	1 h	6.84–19.88 (10.61)	10.32–33.81 (23.5)	20.23–57.05 (26.55)	0.001	0.01	0.009	NS
	1 day	11–11.86 (11.6)	12.96–39.86 (36.23)	18.35–53.91 (31.32)	< 0.001	0.007	0.01	NS
	7 days	12.83–17.13 (14.26)	17.46–43.26 (39.6)	19.22–63.38 (30.21)	< 0.001	0.01	0.01	NS
	14 days	7.26–10.23 (8.13)	10.63–24.04 (19.75)	10.63–38.73 (15.23)	< 0.001	0.01	0.02	NS

Note: **Bold p-values indicate statistically significant differences** ($p < 0.05$). "NS" denotes non-significant differences.

TEGDMA Release

Under 6-second curing, TEGDMA release increased with increasing attachment height in the FSF, TBXT, and Z350 composites, particularly at 1, 7, and 14 days ($p < 0.05$), whereas in the TEP composite, height-related differences were observed only at the 1-hour time point ($p < 0.001$). When the curing time was extended to 12 seconds, a more consistent height-dependent pattern emerged, especially in the TBXT and TEP composites, in which TEGDMA release increased significantly from 3 mm to 5 mm across all evaluated time points ($p < 0.01$), while FSF and Z350 composites exhibited significant height-related differences mainly at 1 and 7 days, with no significant differences at certain early or late time points (Tables 2–3).

BISGMA Release

Under 6-second curing, BISGMA release increased with greater height in the FSF, TBXT, and TEP composites at most time points ($p < 0.05$), whereas in the Z350 composite, height-related differences were limited and became significant only at later time points (7 and 14 days). Following 12-second curing, a clear height-dependent increase in BISGMA release was observed in the TBXT and TEP composites at all evaluated time points ($p < 0.001$), while FSF and Z350 composites demonstrated a more moderate and time-dependent height effect (Tables 2–3).

Intragroup Comparison of TEGDMA and Bis-GMA Release Over Time

Intragroup analysis revealed significant time-dependent changes in TEGDMA and Bis-GMA release at all tested heights under both 6 s and 12 s light-curing conditions for all composites ($p < 0.001$). In general, prolongation of light-curing time to 12 s resulted in lower early monomer release and a more stable release profile compared with 6 s curing. Under 6 s curing, TEGDMA release from FSF differed significantly mainly between the 1-hour measurement and later time points (7 and 14 days), while the 1 hour–1 day comparison was not significant ($p > 0.05$). Similarly, Z350 showed a significant increase in TEGDMA release from 1 hour to later time points, whereas in TEP, TEGDMA release was highest at early time points and decreased significantly over time. For TBXT, both TEGDMA and Bis-GMA release generally peaked at 7 days and decreased by 14 days under 6 s curing. Across all composites, prolongation of curing time to 12 s consistently resulted in lower TEGDMA release values at early time points, with Z350 showing TEGDMA release below detection limits at 1 hour. Bis-GMA release showed significant time-dependent differences in all composites, mainly between early and late intervals, with FSF and TEP exhibiting fewer significant differences between adjacent time points under 12 s curing (Tables 4,5,6,7).

Table 4
Intragroup comparison of TEGDMA and Bis-GMA release from FSF composite placed at different thicknesses under 6 s and 12 s light-curing conditions at different time points

Curing Time	Monomer	Thickness	1 h (min-max, median)	1 day (min-max, median)	7 days (min-max, median)	14 days (min-max, median)	Overall p	1h–1d	1h–7d	1h–14d	1d–7d	1d–14d	7d–14d
6 s	TEGDMA	3 mm	2.99–6.33 (4.64)	3.09–4.61 (3.25)	2.44–3.64 (3.15)	0.40–0.83 (0.72)	< 0.001	NS	0.016	0.002	NS	0.002	0.002
		4 mm	3.84–6.26 (4.82)	4.45–7.23 (5.88)	2.62–3.14 (2.84)	0.44–0.74 (0.59)	< 0.001	NS	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
		5 mm	4.50–21.62 (8.36)	4.75–5.75 (5.08)	3.13–3.77 (3.57)	0.70–0.96 (0.88)	< 0.001	NS	0.002	0.002	0.002	0.002	0.002
	Bis-GMA	3 mm	2.99–6.33 (4.64)	3.09–4.61 (3.25)	2.44–3.64 (3.15)	0.40–0.83 (0.72)	< 0.001	NS	0.016	0.002	NS	0.002	0.002
		4 mm	3.84–6.26 (4.82)	4.45–7.23 (5.88)	2.62–3.14 (2.84)	0.44–0.74 (0.59)	< 0.001	NS	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
		5 mm	4.50–21.62 (8.36)	4.75–5.75 (5.08)	3.13–3.77 (3.57)	0.70–0.96 (0.88)	< 0.001	NS	0.002	0.002	0.002	0.002	0.002
12 s	TEGDMA	3 mm	1.13–2.88 (2.24)	1.03–1.45 (1.26)	0.72–1.08 (0.81)	0.17–0.83 (0.37)	< 0.001	< 0.001	< 0.001	< 0.001	0.01	< 0.001	0.002
		4 mm	1.41–3.01 (2.68)	1.51–1.93 (1.73)	1.01–1.23 (1.09)	0.18–0.72 (0.37)	< 0.001	0.01	0.004	< 0.001	0.04	0.003	0.02
		5 mm	1.46–2.71 (1.60)	1.36–1.85 (1.62)	1.04–1.44 (1.26)	0.21–0.85 (0.51)	< 0.001	0.03	0.008	< 0.001	NS	0.01	0.02
	Bis-GMA	3 mm	5.52–14.43 (10.18)	7.07–13.49 (10.32)	10.72–12.73 (12.05)	8.33–11.12 (10.04)	0.001	NS	0.004	NS	0.01	NS	0.003
		4 mm	6.46–12.19 (10.68)	8.65–11.44 (10.04)	11.90–13.34 (13.12)	9.92–11.69 (10.57)	< 0.001	NS	< 0.001	NS	< 0.001	0.01	0.001
		5 mm	6.56–11.72 (6.72)	8.25–11.17 (10.11)	12.34–16.11 (15.36)	10.26–12.30 (11.56)	< 0.001	NS	< 0.001	0.008	< 0.001	0.003	0.001

NS: not significant; LOD: limit of detection. Overall p-values were obtained using intragroup repeated-measures analysis with post hoc pairwise comparisons.

Table 5
Intragroup comparison of TEGDMA and Bis-GMA release from TBXT composite placed at different thicknesses under 6 s and 12 s light-curing conditions at different time points

Curing Time	Monomer	Thickness	1 h (min-max, median)	1 day (min-max, median)	7 days (min-max, median)	14 days (min-max, median)	Overall p	1h–1d	1h–7d	1h–14d	1d–7d	1d–14d	7d–14d
6 s	TEGDMA	3 mm	0.90–1.16 (1.04)	0.62–1.36 (1.27)	0.82–1.32 (1.56)	0.40–0.75 (0.57)	< 0.001	NS	NS	0.002	NS	0.01	0.002
		4 mm	1.09–1.32 (1.26)	1.27–1.94 (1.48)	1.22–2.20 (2.03)	0.46–1.02 (0.91)	< 0.001	0.007	NS	0.002	NS	0.002	0.002
		5 mm	1.42–1.64 (1.53)	1.27–2.19 (1.90)	1.31–2.39 (2.54)	0.70–1.27 (0.94)	< 0.001	NS	NS	0.002	NS	0.003	0.002
	Bis-GMA	3 mm	55.93–71.01 (65.88)	62.02–85.78 (77.99)	62.40–90.78 (82.66)	35.38–52.40 (48.62)	< 0.001	NS	NS	0.002	NS	0.002	0.002
		4 mm	61.26–90.46 (66.80)	84.10–122.44 (117.16)	92.75–145.45 (116.41)	59.88–89.94 (74.83)	< 0.001	0.03	0.002	NS	NS	0.03	0.002
		5 mm	71.27–94.45 (91.88)	98.37–127.28 (123.81)	104.07–150.65 (140.57)	68.01–95.49 (90.80)	< 0.001	0.002	0.002	NS	NS	0.002	0.002
12 s	TEGDMA	3 mm	0.36–0.64 (0.46)	1.17–1.65 (1.07)	1.28–1.80 (1.10)	0.24–0.47 (0.36)	< 0.001	0.002	0.002	NS	NS	0.002	0.002
		4 mm	0.41–0.88 (0.63)	1.15–1.69 (1.35)	1.57–2.50 (1.61)	0.53–0.73 (0.59)	< 0.001	0.002	0.002	NS	0.004	0.002	0.002
		5 mm	0.77–1.00 (0.90)	1.21–1.95 (1.55)	2.38–2.71 (2.05)	0.52–1.10 (0.80)	< 0.001	0.002	0.002	NS	0.002	0.002	0.002
	Bis-GMA	3 mm	19.68–28.65 (21.28)	38.92–55.18 (52.27)	52.15–58.54 (55.55)	24.84–28.57 (25.59)	< 0.001	0.002	0.002	NS	NS	0.002	0.002
		4 mm	26.00–76.66 (27.93)	42.74–57.62 (49.21)	52.98–77.22 (75.80)	26.00–36.19 (34.12)	< 0.001	0.03	0.02	NS	0.01	0.002	0.002
		5 mm	24.73–34.18 (29.40)	47.51–61.28 (51.00)	70.13–81.48 (73.13)	32.70–40.92 (37.18)	< 0.001	0.002	0.002	0.008	0.002	0.002	0.002

NS: not significant; LOD: limit of detection. Overall p-values were obtained using intragroup repeated-measures analysis with post hoc pairwise comparisons.

Table 6
Intragroup comparison of TEGDMA and Bis-GMA release from Z350 composite placed at different thicknesses under 6 s and 12 s light-curing conditions at different time points

Curing Time	Monomer	Thickness	1 h (min-max, median)	1 day (min-max, median)	7 days (min-max, median)	14 days (min-max, median)	Overall p	1h–1d	1h–7d	1h–14d	1d–7d	1d–14d	7d–14d
6 s	TEGDMA	3 mm	0.208–0.425 (0.262)	0.491–0.730 (0.637)	0.595–0.892 (0.743)	0.140–0.225 (0.203)	< 0.001	0.002	0.002	0.008	0.03	0.002	0.002
		4 mm	0.237–0.412 (0.273)	0.550–0.802 (0.718)	0.957–1.122 (1.065)	0.281–0.343 (0.315)	< 0.001	0.002	0.002	NS	0.002	0.002	0.002
		5 mm	0.260–0.335 (0.295)	0.557–0.759 (0.714)	0.968–1.329 (1.051)	0.228–0.419 (0.369)	< 0.001	0.002	0.002	NS	0.002	0.002	0.002
	Bis-GMA	3 mm	7.63–15.10 (11.14)	11.57–22.65 (19.01)	3.46–5.90 (5.05)	2.11–11.28 (8.91)	< 0.001	0.01	0.002	NS	0.002	0.002	0.03
		4 mm	6.34–17.48 (8.33)	12.11–19.46 (16.11)	5.21–6.94 (5.85)	8.26–11.49 (10.59)	< 0.001	NS	0.01	NS	0.002	0.002	0.002
		5 mm	7.66–14.71 (10.95)	13.39–15.94 (14.74)	4.45–8.81 (6.35)	8.54–14.99 (11.27)	< 0.001	0.008	0.01	NS	0.002	NS	0.003
12 s	TEGDMA	3 mm	<LOD	0.245–0.316 (0.26)	0.473–0.656 (0.531)	0.289–0.449 (0.105)	< 0.001	0.001	0.001	0.001	0.002	0.008	0.002
		4 mm	<LOD	0.205–0.383 (0.327)	0.486–0.759 (0.599)	0.303–0.588 (0.265)	< 0.001	0.001	0.001	0.001	0.002	NS	0.01
		5 mm	<LOD	0.329–0.626 (0.402)	2.855–4.156 (0.923)	0.243–0.931 (0.157)	< 0.001	0.001	0.001	0.001	0.002	NS	0.002
	Bis-GMA	3 mm	0.47–1.809 (1.261)	0.773–1.221 (1.069)	1.945–3.225 (2.526)	0.973–2.662 (2.409)	< 0.001	NS	0.002	0.02	0.002	0.02	NS
		4 mm	0.825–2.505 (1.421)	1.918–3.046 (2.522)	1.918–3.046 (2.522)	2.081–2.913 (2.41)	< 0.001	0.006	0.006	0.02	NS	NS	NS
		5 mm	7.664–14.711 (10.95)	2.855–4.156 (3.36)	2.855–4.156 (3.36)	2.484–3.532 (3.028)	< 0.001	0.002	0.002	0.002	NS	NS	NS

NS: not significant; LOD: limit of detection. Overall p-values were obtained using intragroup repeated-measures analysis with post hoc pairwise comparisons.

Table 7
Intragroup comparison of TEGDMA and Bis-GMA release from TEP composite placed at different thicknesses under 6 s and 12 s light-curing conditions at different time points

Curing Time	Monomer	Thickness	1 h (min-max, median)	1 day (min-max, median)	7 days (min-max, median)	14 days (min-max, median)	Overall p	1h–1d	1h–7d	1h–14d	1d–7d	1d–14d	7d–14d
6 s	TEGDMA	3 mm	4.86–50.78 (48.88)	34.18–54.29 (50.2)	15.07–20.25 (19.15)	0.724–2.005 (1.091)	< 0.001	NS	0.03	0.002	0.002	0.002	0.002
		4 mm	33.76–74.72 (53.32)	30.77–67.86 (60.91)	11.27–22.73 (21.77)	0.269–2.893 (0.749)	< 0.001	0.002	0.002	0.002	0.002	0.002	0.002
		5 mm	55.83–107.89 (71.21)	48.96–69.69 (58.7)	11.96–25.73 (22.99)	0.506–1.763 (0.827)	< 0.001	NS	0.002	0.002	0.002	0.002	0.002
	Bis-GMA	3 mm	40.62–95.37 (77.2)	87.92–135.32 (129.06)	67.42–95.02 (75.42)	23.74–27.46 (26.42)	< 0.001	0.03	NS	0.002	0.02	0.002	0.002
		4 mm	44.43–119.22 (89.61)	75.48–166.53 (156.42)	75.96–88.68 (84.69)	17.06–29.61 (27.18)	< 0.001	NS	NS	0.002	NS	0.002	0.002
		5 mm	96.38–179.66 (125.03)	118.74–162.77 (138.27)	93.09–124.74 (96.02)	14.01–318.58 (32.12)	< 0.001	NS	NS	0.03	0.01	0.03	0.03
12 s	TEGDMA	3 mm	4.79–10.07 (6.56)	6.17–6.73 (6.45)	4.32–5.65 (4.99)	2.0–2.43 (0.223)	< 0.001	NS	NS	0.002	0.002	0.002	0.002
		4 mm	6.13–21.39 (15.74)	6.8–17.6 (16.67)	5.06–13.72 (13.36)	2.24–5.59 (0.459)	< 0.001	NS	NS	0.002	NS	0.002	0.03
		5 mm	10.28–33.65 (14.26)	8.66–28.13 (14.8)	5.28–24.22 (8.07)	2.36–10.62 (0.344)	0.002	NS	NS	0.02	NS	0.03	NS
	Bis-GMA	3 mm	6.84–19.88 (10.61)	11–11.86 (11.6)	12.83–17.13 (14.26)	7.26–10.23 (8.13)	< 0.001	NS	NS	NS	0.002	0.002	0.002
		4 mm	10.32–33.81 (23.5)	12.96–39.86 (36.23)	17.46–43.26 (39.6)	10.63–24.04 (19.75)	0.05	–	–	–	–	–	–
		5 mm	20.23–57.05 (26.55)	18.35–53.91 (31.32)	19.22–63.38 (30.21)	10.63–38.73 (15.23)	0.09	–	–	–	–	–	–

NS: not significant; LOD: limit of detection. Overall p-values were obtained using intragroup repeated-measures analysis with post hoc pairwise comparisons

Intergroup comparison of TEGDMA and BISGMA release at different time points for composite types placed in varying heights under 6 s and 12 s light curing

Kruskal–Wallis analysis demonstrated statistically significant differences in both TEGDMA and BIS-GMA release among composite materials across all specimen heights (3, 4, and 5 mm), curing times (6 s and 12 s), and evaluation periods (1 hour, 1 day, 7 days, and 14 days), with most comparisons showing $p < 0.001$(Table 8).

Table 8
Intergroup comparison of TEGDMA and BISGMA elutions at different time points for composite types placed in varying length under 6 s and 12 s light curin Wallis and post-hoc test results)

Length	Curing	Time	Kruskal–Wallis *p value* (TEGDMA)	FSF–TBXT	FSF–Z350	FSF–TEP	TBXT–Z350	TBXT–TEP	Z350–TEP	Kruskal–Wallis *p value* (BISGMA)	FSF–TBXT	FSF–Z350	FSF–TEP	TBXT–Z350	TBX–TEP
3 mm	6 s	1 h	< 0.001	0.002	0.002	0.006	0.008	0.002	0.002	< 0.001	0.002	0.002	0.002	0.002	0.00
		1 day	< 0.001	0.002	0.002	0.002	0.002	0.002	0.002	< 0.001	0.002	NS	0.002	0.002	0.00
		7 days	< 0.001	0.002	0.002	0.002	0.002	0.002	0.002	< 0.001	0.002	0.002	0.006	0.002	0.00
		14 days	< 0.001	0.006	0.002	0.020	0.002	0.002	0.002	< 0.001	0.002	0.002	0.002	0.002	NS
	12 s	1 h	< 0.001	NS	0.010	0.002	0.002	0.002	0.002	< 0.001	NS	0.002	0.002	0.002	0.00
		1 day	< 0.001	0.002	0.002	0.002	0.002	0.002	0.002	< 0.001	0.002	0.002	0.002	0.002	0.00
		7 days	< 0.001	0.002	0.006	0.002	0.008	NS	0.002	< 0.001	0.002	0.002	NS	0.002	0.00
		14 days	< 0.001	NS	0.001	NS	0.002	0.002	0.002	< 0.001	0.002	0.002	NS	0.002	0.00
4 mm	6 s	1 h	< 0.001	0.002	0.002	0.002	0.002	0.002	0.002	< 0.001	0.002	0.002	0.002	0.002	0.00
		1 day	< 0.001	0.002	0.002	0.002	0.002	0.002	0.002	< 0.001	0.002	0.002	0.002	0.002	0.00
		7 days	< 0.001	0.002	0.002	0.002	0.002	0.002	0.002	< 0.001	0.002	0.002	0.002	0.002	0.00
		14 days	< 0.01	NS	0.002	NS	0.002	NS	NS	< 0.001	NS	0.002	NS	0.002	0.00
	12 s	1 h	< 0.001	0.002	0.010	0.002	0.002	0.006	0.002	< 0.001	0.002	0.002	0.002	0.002	0.00
		1 day	< 0.001	NS	0.002	0.002	0.002	0.002	0.002	< 0.001	0.002	0.002	0.002	0.002	0.00
		7 days	< 0.001	0.002	0.002	0.002	0.002	NS	0.002	< 0.001	0.002	NS	0.002	0.002	0.00
		14 days	< 0.001	0.002	0.002	0.002	0.002	0.002	0.002	< 0.001	0.002	0.002	0.002	0.002	0.00
5 mm	6 s	1 h	< 0.001	0.002	0.002	0.002	0.002	0.002	0.002	< 0.001	0.002	0.002	0.002	0.002	0.00
		1 day	< 0.001	0.002	0.002	0.002	0.002	0.002	0.002	< 0.001	0.002	0.002	0.002	0.002	0.00
		7 days	< 0.001	0.002	0.002	0.002	0.002	0.002	0.002	< 0.001	0.002	NS	0.002	0.002	0.00
		14 days	< 0.01	NS	0.002	NS	0.002	0.002	0.009	< 0.001	NS	0.002	NS	0.002	0.00
	12 s	1 h	< 0.001	NS	0.002	0.002	0.002	0.002	0.002	< 0.001	NS	0.002	0.002	0.002	0.00
		1 day	< 0.001	0.002	0.002	0.002	0.002	0.002	0.002	< 0.001	0.002	0.002	0.002	0.002	0.00
		7 days	< 0.001	0.010	NS	0.002	0.007	0.002	0.002	< 0.001	0.010	NS	0.002	0.007	0.00
		14 days	< 0.001	0.002	0.002	NS	0.002	0.002	0.002	< 0.001	0.002	0.002	NS	0.002	0.00

Note: NS – Not significant (p > 0.05); bold values indicate statistically significant differences (p < 0.05).

3 mm Specimen Height

At a specimen height of 3 mm, samples cured for 6 seconds exhibited significant inter-group differences in both TEGDMA and BIS-GMA release at all time points ($p < 0.001$). Pairwise comparisons revealed significant differences particularly for the **FSF–TEP**, **FSF–Z350**, and **TBXT–TEP** comparisons (mostly $p = 0.002$). When a curing time of 12 seconds was applied, overall group differences remained significant ($p < 0.001$); however, statistical significance was lost in some pairwise comparisons (e.g., **FSF–TBXT** and **Z350–TEP**) at specific time points (NS). This finding suggests that extended curing partially attenuates inter-material differences.

4 mm Specimen Height

At a specimen height of 4 mm, samples cured for 6 seconds showed statistically significant differences in both TEGDMA and BIS-GMA release across all pairwise comparisons during the early and intermediate evaluation periods (1 hour, 1 day, and 7 days) ($p < 0.001$). At 14 days, statistical significance was lost in some comparisons, particularly **FSF–TBXT**, **TBXT–Z350**, and **Z350–TEP**, indicating a potential reduction in inter-material differences over time. In the 4 mm samples cured for 12 seconds, overall group differences were maintained across all evaluation periods ($p < 0.001$), and the majority of pairwise comparisons remained statistically significant.

5 mm Specimen Height

At a specimen height of 5 mm, samples cured for 6 seconds demonstrated pronounced inter-group differences at all time points ($p < 0.001$). Nevertheless, at 14 days, statistical significance was lost in certain pairwise comparisons, particularly **FSF–TBXT** and **TBXT–Z350**. With a curing time of 12 seconds, group differences in both TEGDMA and BIS-GMA release became more consistent, and most pairwise comparisons remained statistically significant across all time points ($p < 0.001$). However, a limited number of comparisons (e.g., some pairwise analyses at 7 days) showed loss of statistical significance (Table 8).

DISCUSSION

Clear aligner therapy can be applied for orthodontic treatment across a wide age range, from childhood to adulthood. The average treatment duration with clear aligners is approximately 22.8 months. In 94% of cases, a refinement phase is required, with an average of 2.5 refinement stages per patient [18]. During the course of treatment, new attachments are bonded both at the initiation of therapy and during the refinement phase to facilitate the planned tooth movements. The present study was designed to evaluate the time-dependent release of residual monomers from different light-cured composite materials used for clear aligner attachments under in-vitro conditions at different curing times. Considering that incomplete polymerization and material degradation may lead to monomer elution with potential biological risks, evaluating the effects of curing time and material type is important. To the best of our knowledge, this is the first study to comprehensively evaluate time-dependent monomer release from different composite materials at different curing times following attachment bonding in clear aligner therapy.

The oxygen inhibition layer contains unpolymerized monomers [19], which can be eluted. The removal of the oxygen inhibition layer leads to fewer eluted monomers. Effective methods prevent oxygen contact, e.g., glycerin gel or mylar strips, and mechanical methods, e.g., specimen polishing with a defined removal of 0.2 mm are recommended [20, 21]. During routine orthodontic treatment with clear aligners, attachments are bonded using clear aligner templates. During this procedure, the attachment surface is covered by the aligner template during light curing, thereby largely isolating the composite from oxygen; consequently, the formation of an oxygen inhibition layer is minimal. To simulate this effect under in vitro conditions, a Mylar strip was placed over the composite during light curing, thereby decreasing the formation of an oxygen-inhibited layer. Besides the oxygen inhibition layer, the surface roughness of cured composite may influence monomer elution. Hampe et.al. recommend the polishing the composite surface after curing to reduce the monomer release [6]. However, polishing the attachment surfaces is not clinically applicable in orthodontic practice, as it may alter the shape of the attachments and consequently affect the predictability of the planned tooth movement. In this study, our objective was to examine the release of unpolymerized monomers resulting from different light-curing exposure.

The number and design of attachments in clinical practice vary according to the individual treatment plan, and the mean number of attachments per arch has been reported to be approximately six [22]. Composite loading occurs simultaneously during the attachment bonding appointment. Also surface area has a significant influence on the amount of eluted monomers [23], therefore in this study the width (2 mm) and depth (1 mm) of rectangular attachments were kept constant, while the heights (3, 4, 5 mm) were varied to measure the amounts of monomer release, aiming to volumetrically calculate value of monomer release. This approach was chosen to provide a standardized comparison and ensure consistent measurement conditions across all samples.

The present study demonstrated that monomer release from resin composites is influenced by light-curing duration, material height, and composite type. The monomer elution of elements and the cytotoxicity of composite resins are strongly influenced by polymerization parameters, such as the type of light-curing unit, total energy density, power density, irradiation time, and curing mode [24]. Longer curing times (12 s) markedly reduced TEGDMA and BIS-GMA elution, indicating more complete polymerization and potentially enhanced biocompatibility. Restorations with increased length exhibited higher monomer release, particularly under shorter curing conditions, highlighting the need for extended curing in clinical practice.

Differences between composites were evident: FSF and Z350 showed lower monomer release, whereas TEP and TBXT, especially regarding BIS-GMA, exhibited higher elution, likely due to variations in chemical composition, monomer content, and filler load. TEGDMA consistently eluted faster and in greater amounts than BIS-GMA, reflecting its lower molecular weight and higher mobility.

Monomer release peaked within the first 24 hours and stabilized thereafter, emphasizing the critical period for residual monomer diffusion. These findings underscore the importance of tailoring restoration height, composite selection, and curing protocols to minimize monomer exposure, particularly in sensitive patient populations. While conducted in vitro, the results provide practical guidance for optimizing polymerization strategies to improve the safety and longevity of composite restorations.

In light of this study, the bonding of attachments for clear aligner therapy may be considered a potential source of monomer exposure. Although the toxicological literature on monomers are extensive, a definitive dose–response threshold has not yet been clearly established. According to the “low-dose” hypothesis, biological effects may occur at exposure levels far below those considered safe, due to a non-monotonic dose–response relationship. Reducing exposure to residual monomers as much as possible is therefore advisable [25]. In this context, optimizing biomechanical treatment planning to minimize the total number of attachments, where clinically feasible, may contribute to lowering cumulative monomer exposure. Also optimal light-curing protocols,

particularly with extended curing times, enhance the degree of conversion [26, 27]. In clinical practice, excess adhesive material remaining around attachments should be carefully removed. Finally, avoiding the use of adhesives containing BPA derivatives may further reduce BPA exposure.

CONCLUSION

The light-curing duration, attachment heinght, and different composites have a significant impact on the amount of released monomers. Further toxicological studies are required to clarify the safety of other monomers commonly used in resin composites. Composite materials exhibiting minimal cytotoxicity may be preferred, and extended light-curing durations are recommended to improve polymerization efficiency and minimize residual monomer elution.

Abbreviations

FSF
3M™ Filtek™ Supreme Flowable Restorative
TBXT
3M™ Transbond™ XT Light Cure Adhesive
TEP
Tokuyama Estelite Posterior
Z350
3M™ Filtek™ Z350 XT Universal Restorative

Declarations

Conflict of interest:

The authors declare no conflict of interest related to this study.

This study has not been previously presented at any scientific meeting.

Ethics approval

Ethics committee approval was not required for this study due to its non-interventional design. The study was conducted in accordance with the principles of the Declaration of Helsinki.

Consent for publication

Not applicable.

Competing Interests

The authors declare that they have no competing interests.

Funding:

This research received financial support from the Scientific Research Projects Coordination Unit (BAP) of Bezmialem Vakıf Üniversitesi (Project No: 20240224).

Author Contribution

N.K. conceptualized and designed the study, supervised data collection, and critically revised the manuscript.Ş.Ş contributed to study design and data interpretation and critically reviewed the manuscript.A.K. performed data collection, statistical analysis.G.T. contributed to data organization.All authors read and approved the final manuscript.

Acknowledgments:

None

Ethics: Ethics committee approval was not required for this study due to its non-interventional design.

Data Availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

References

1. Putrino A, Barbato E, Galluccio G. Clear aligners: between evolution and efficiency—a scoping review. Int J Environ Res Public Health. 2021;18:2870.
2. Lynch NM, Shroff B, Carrico CK, Sawicki V, Sabol M, Lindauer SJ. Clear aligner therapy in the mixed dentition: indications and practitioner perspectives. Am J Orthod Dentofac Orthop. 2023;164:172–82.
3. Papadimitriou A, Mousoulea S, Gkantidis N, Kloukos D. Clinical effectiveness of Invisalign orthodontic treatment: a systematic review. Prog Orthod. 2018;19:1–24.
4. Garino F, Castroflorio T, Daher S, Ravera S, Rossini G, Cugliari G, et al. Effectiveness of composite attachments in controlling upper-molar movement with aligners. J Clin Orthod. 2016;50:341–7.
5. Söderholm KJ, Mariotti A. Bis-GMA–based resins in dentistry: are they safe? J Am Dent Assoc. 1999;130:201–9.
6. Hampe T, Wiessner A, Frauendorf H, Alhussein M, Karlovsky P, Bürgers R, et al. Monomer release from dental resins: the current status on study setup, detection and quantification for in vitro testing. Polym (Basel). 2022;14:1790.
7. Shimokawa CAK, Turbino ML, Giannini M, Braga RR, Price RB. Effect of light curing units on the polymerization of bulk fill resin-based composites. Dent Mater. 2018;34:1211–21.
8. Hayashi M, Yamada T, Lynch CD, Wilson NH. Teaching of posterior composites in dental schools in Japan—30 years and beyond. J Dent. 2018;76:19–23.
9. Bettencourt AF, Neves CB, de Almeida MS, Pinheiro LM, Oliveira SA, Lopes LP, et al. Biodegradation of acrylic based resins: a review. Dent Mater. 2010;26:e171–80.
10. Fenichel P, Chevalier N, Brucker-Davis F. Bisphenol A: an endocrine and metabolic disruptor. Ann Endocrinol (Paris). 2013;74:211–20.
11. Rochester JR. Bisphenol A and human health: a review of the literature. Reprod Toxicol. 2013;42:132–55.
12. Samanidou V, Livadiotou D, Palaghias G, Papadoyannis I. A simple and rapid HPLC method for the direct determination of residual monomers released from dental polymeric materials in blood serum and urine. J Liq Chromatogr Relat Technol. 2015;38:201–7.
13. Pratap B, Gupta RK, Bhardwaj B, Nag M. Resin based restorative dental materials: characteristics and future perspectives. Jpn Dent Sci Rev. 2019;55:126–38.
14. Sideridou ID, Achilias DS. Elution study of unreacted Bis-GMA, TEGDMA, UDMA, and Bis-EMA from light-cured dental resins and resin composites using HPLC. J Biomed Mater Res B Appl Biomater. 2005;74:617–26.
15. Viljanen EK, Langer S, Skrifvars M, Vallittu PK. Analysis of residual monomers in dendritic methacrylate copolymers and composites by HPLC and headspace-GC/MS. Dent Mater. 2006;22:845–51.
16. Pulgar R, Olea-Serrano MF, Novillo-Fertrell A, Rivas A, Pazos P, Pedraza V, et al. Determination of bisphenol A and related aromatic compounds released from bis-GMA-based composites and sealants by high performance liquid chromatography. Environ Health Perspect. 2000;108:21–7.
17. Dasy H, Dasy A, Asatrian G, Rózsa N, Lee HF, Kwak JH. Effects of variable attachment shapes and aligner material on aligner retention. Angle Orthod. 2015;85:934–40.
18. Kravitz ND, Dalloul B, Zaid YA, Shah C, Vaid NR. What percentage of patients switch from Invisalign to braces? A retrospective study evaluating the conversion rate, number of refinement scans, and length of treatment. Am J Orthod Dentofac Orthop. 2023;163:526–30.
19. Kim JS, Choi YH, Cho BH, Son HH, Lee IB, Um CM, et al. Effect of light-cure time of adhesive resin on the thickness of the oxygen-inhibited layer and the microtensile bond strength to dentin. J Biomed Mater Res B Appl Biomater. 2006;78:115–23.
20. Bezgin T, Cimen C, Ozalp N. Evaluation of residual monomers eluted from pediatric dental restorative materials. Biomed Res Int. 2021;2021:6316171.
21. Park HH, Lee IB. Effect of glycerin on the surface hardness of composites after curing. J Korean Acad Conserv Dent. 2011;36:483–9.
22. Al-Nadawi M, Kravitz ND, Hansa I, Makki L, Ferguson DJ, Vaid NR. Effect of clear aligner wear protocol on the efficacy of tooth movement: a randomized clinical trial. Angle Orthod. 2021;91:157–63.
23. Hampe T, Wiessner A, Frauendorf H, Alhussein M, Karlovsky P, Bürgers R, et al. Monomer release from dental resins: the current status on study setup, detection and quantification for in vitro testing. Polym (Basel). 2022;14:1790.
24. Sigusch BW, Völpel A, Braun I, Uhl A, Jandt KD. Influence of different light curing units on the cytotoxicity of various dental composites. Dent Mater. 2007;23:1342–8.
25. Kloukos D, Pandis N, Eliades T. Bisphenol-A and residual monomer leaching from orthodontic adhesive resins and polycarbonate brackets: a systematic review. Am J Orthod Dentofac Orthop. 2013;143(Suppl 4):S104–e122.
26. Sunitha C, Kailasam V, Padmanabhan S, Chitharanjan AB. Bisphenol A release from an orthodontic adhesive and its correlation with the degree of conversion on varying light-curing tip distances. Am J Orthod Dentofac Orthop. 2011;140:239–44.
27. Purushothaman D, Kailasam V, Chitharanjan AB. Bisphenol A release from orthodontic adhesives and its correlation with the degree of conversion. Am J Orthod Dentofac Orthop. 2015;147:29–36.

Figures

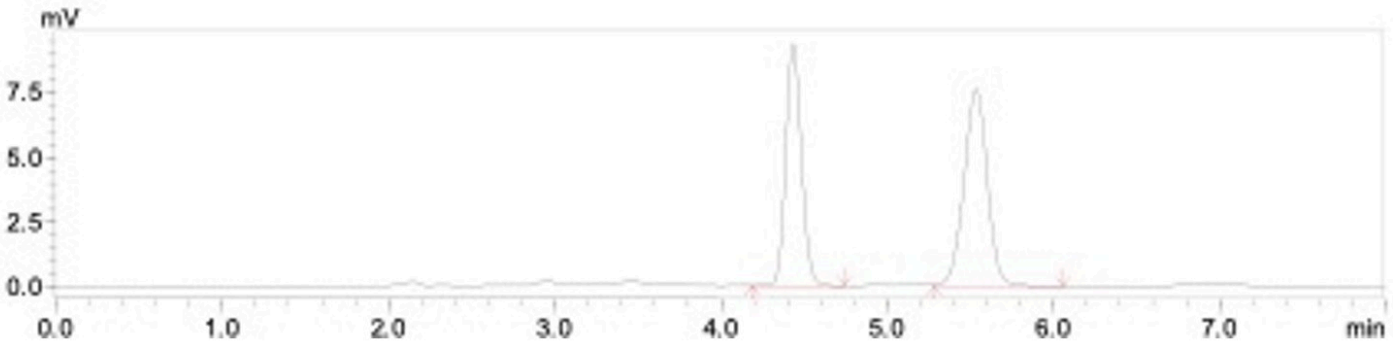


Figure 1

The chromatogram of standard solution of BISGMA and TEGDMA (30.0 µg/mL).