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Enhancement of Flexural and Compressive Strength of Methacrylate-Based Composites Through Glass Fiber Reinforcement

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Abstract

The phase-down of mercury-containing amalgam under the Minamata Convention has created a need for mercury-free restorative materials capable of withstanding high masticatory forces in posterior teeth. Resin-based composites are the preferred alternative; however, those formulated with bisphenol A-glycidyl methacrylate and urethane dimethacrylate often exhibit high water sorption, polymerization shrinkage, and cytotoxicity, compromising their long-term clinical performance. Bisphenol A ethoxylated dimethacrylate (BisEMA) offers reduced water sorption and lower cytotoxicity, yet its mechanical strength may be insufficient for posterior applications without reinforcement. This in vitro study aimed to enhance the flexural and compressive properties of a BisEMA/triethylene glycol dimethacrylate (80:20 wt%) composite through E-glass fiber incorporation at 3 wt% and 5 wt%. Specimens were fabricated according to ISO 4049 standards for flexural (25 × 2 × 2 mm) and compressive (4 × 6 mm) testing, with Tetric N Ceram, Charisma Smile, and Brilliant NG serving as controls. The 5 wt% fiber group achieved significantly higher flexural strength (82.94 ± 4.64 MPa) than the 3 wt% fiber group (75.52 ± 6.70 MPa, p = 0.0109), with values comparable to Tetric N Ceram and Charisma Smile. Compressive strength for the 5 wt% fiber group (124.31 ± 27.69 MPa) exceeded Brilliant NG but was not significantly different from the 3 wt% fiber group (101.97 ± 22.50 MPa, p = 0.0639). One-way ANOVA showed no statistically significant differences in flexural strength among all groups (p > 0.05), while compressive strength differences were more pronounced. These results indicate that E-glass fiber reinforcement improves the mechanical properties of BisEMA-based composites and supports its potential for the development of biocompatible, high-performance posterior restorative materials that address the limitations of existing formulations.

Categories: Advanced Materials
Keywords: bisema-based composites, compressive strength, e-glass fiber reinforcement, flexural strength, posterior restorative materials

Introduction

The phase-out of dental amalgam, driven by the Minamata Convention on Mercury, has intensified global efforts to identify mercury-free restorative materials capable of delivering long-term mechanical reliability in high-stress posterior regions [1]. Posterior teeth are subjected to significant occlusal forces-often exceeding 700 N-making fracture resistance, fatigue durability, and marginal integrity critical to clinical success [2]. Resin-based composites have largely replaced amalgam in restorative dentistry due to their superior aesthetics, adhesive capability, and conservative preparation requirements [3,4]. However, despite decades of formulation improvements, these materials remain susceptible to wear, fracture, marginal leakage, and secondary caries in load-bearing applications [5].

Most commercial composites rely on bisphenol A-glycidyl methacrylate (BisGMA) or urethane dimethacrylate (UDMA) matrices, typically diluted with triethylene glycol dimethacrylate (TEGDMA) to achieve workable viscosity. While effective, these systems have inherent limitations: BisGMA's high viscosity demands diluents that increase polymerization shrinkage stress; UDMA has been associated with cytotoxicity; and TEGDMA contributes to water sorption, hydrolytic degradation, and reduced fatigue resistance [6,7]. Clinically, such properties can compromise marginal adaptation and structural integrity, especially under cyclic masticatory loading in posterior restorations [8].

Bisphenol A ethoxylated dimethacrylate (BisEMA) has emerged as a promising alternative matrix due to its lower water sorption, reduced solubility, and potentially lower cytotoxicity compared with BisGMA and UDMA systems [9]. However, its relatively low inherent viscosity, while beneficial for handling, may reduce cross-link density and compromise mechanical performance under high-load conditions. This limitation underscores the need for reinforcement strategies tailored to BisEMA-based composites to meet or exceed

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ISO 4049 standards for flexural strength and compressive resistance in posterior use [10].

E-glass fiber reinforcement is a proven method for improving the mechanical performance of resin composites, offering benefits such as enhanced flexural strength, fracture toughness, and resistance to crack propagation [11]. For optimal reinforcement, fibers must exceed the critical length required for efficient stress transfer-approximately 0.5-1.5 mm for E-glass in dental polymers-and be well-bonded to the resin matrix through silane coupling [12]. Although E-glass fiber reinforcement has been widely investigated in BisGMA- and UDMA-based systems, evidence in BisEMA-based composites remains scarce, particularly regarding the effect of fiber loading percentages on key mechanical outcomes. According to Amiri et al., fiber reinforcement significantly enhances the flexural strength and fracture toughness of resin composites; however, most investigations have been limited to BisGMA- and UDMA-based matrices, with scarce evidence for BisEMA systems [13]. Similarly, Mela et al. highlighted in their review that optimization of fiber concentration and orientation is critical for achieving predictable reinforcement, yet systematic evaluations in BisEMA/TEGDMA formulations remain largely unexplored [14].

These findings reveal a clear knowledge gap in the mechanical characterization of BisEMA/TEGDMA composites with E-glass fiber reinforcement at different weight percentages. To address this, the present study evaluates the effect of 3 wt% and 5 wt% fiber incorporation on flexural and compressive strength, benchmarking against established commercial materials under ISO 4049 standards, thereby providing evidence to guide formulation strategies for posterior restorative applications.

Materials And Methods

The experimental matrix was prepared from BisEMA and TEGDMA in an 80:20 weight ratio. Camphorquinone (0.5 wt%) served as the photoinitiator system [15]. E-glass fibers (average length ≈ 1.5 mm, diameter ≈ 10 μm; exceeding the critical length for stress transfer) [16] were incorporated at loadings of 3 wt% and 5 wt% into the resin by gradual mixing to ensure uniform dispersion and minimize void formation (Table *1*). Cuboidal specimens for flexural testing (25 × 2 × 2 mm) were fabricated according to ISO 4049:2019 using a stainless steel mold. Each specimen was filled in an increments of 2 mm, covered with a Mylar strip and glass slide, and light-cured for 20 seconds per surface with an LED curing unit (≈1000 mW/cm^2; 430-480 nm). Cylindrical specimens for compressive testing (4 mm diameter × 6 mm height) were fabricated using the same curing protocol (Figures *1* and 2) [17]. Flexural strength was measured using a universal testing machine (Instron) with a three-point bending configuration, a 20 mm support span, and a crosshead speed of 1 mm/min (Figure *3*). Flexural strength (σ) was calculated as: $\sigma = 3FL/2bd^2$, where F is maximum load at fracture (N), L is span (mm), b is width (mm), and d is thickness (mm). Compressive strength was measured by loading cylindrical specimens axially between flat platens at 0.5 mm/min until fracture, with compressive strength (σc) calculated as: $\sigma c = AF$, where F is maximum load (N) and A is cross-sectional area (mm^2). Ten specimens per group (Table *2*) were tested for each property. Statistical analysis was performed using SPSS v26. Data normality was confirmed with the Shapiro-Wilk test. One-way ANOVA assessed differences across all groups, followed by Tukey's post hoc test for pairwise comparisons. Welch's t-test compared the 3% and 5% fiber groups directly. Significance was set at $p < 0.05$, and effect sizes were calculated using Cohen's d.

Material Name	Manufacturer	Resin Matrix Composition	Filler Type/Content	E-glass Fiber Content (wt%)
Experimental Composite	Laboratory formulation	BisEMA/TEGDMA (80:20)	Glass fiber + silica	3
Experimental Composite	Laboratory formulation	BisEMA/TEGDMA (80:20)	Glass fiber + silica	5
Tetric N Ceram	Ivoclar Vivadent	BisGMA/UDMA/TEGDMA	Barium glass + ytterbium fluoride + silica	0
Charisma Smile	Kulzer	BisGMA/TEGDMA	Glass ceramic + silica	0
Brilliant NG	Coltene	BisGMA/UDMA	Glass ceramic + silica	0

TABLE 1: Composition and description of experimental and control groups used in the study

Group	Percentage of Glass fiber (%)	Test to be performed
A	3	Flexural
B	5	Flexural
C	3	Compressive
D	5	Compressive

TABLE 2: Composition and description of experimental groups

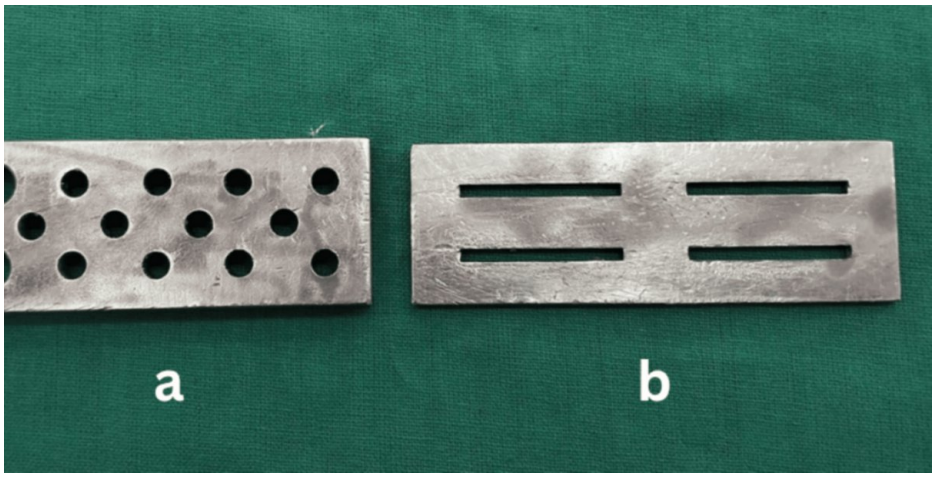

FIGURE 1: (a) Mold for cylindrical specimens to test compressive strength (4 mm diameter and 6 mm height); (b) Mold for rectangular specimens to test flexural strength (25 mm length, 2 mm width and 2 mm thickness)

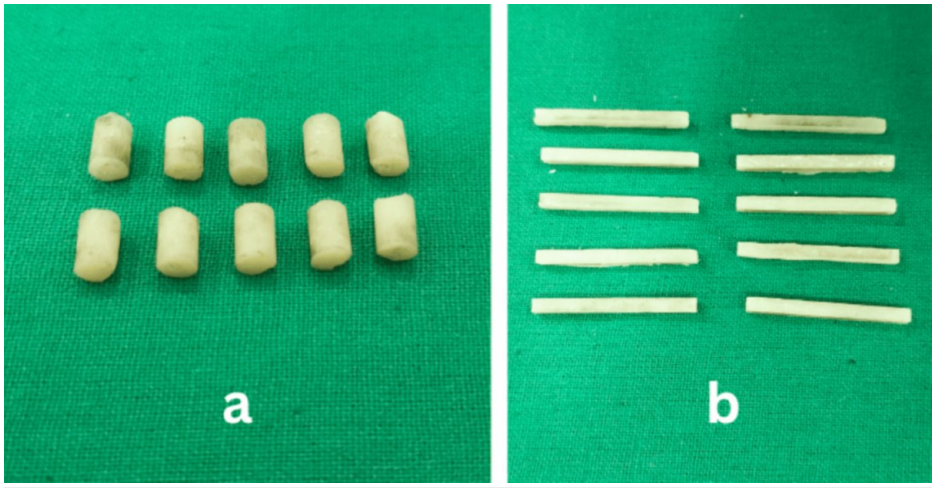

FIGURE 2: (a) Specimens for compressive strength and (b) Specimens for flexural strength

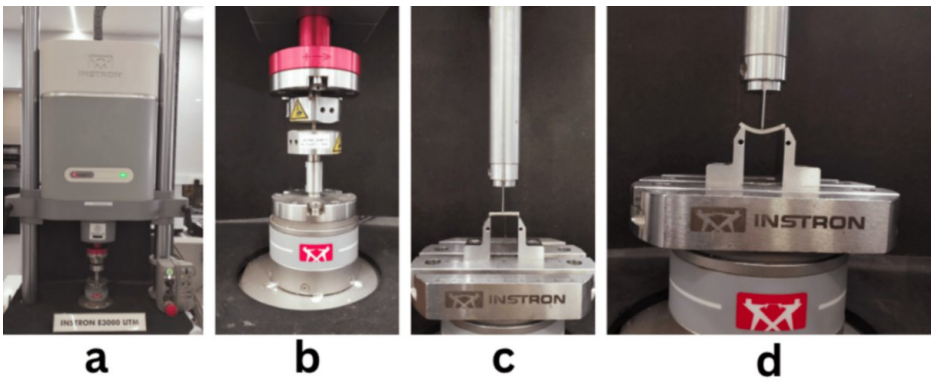

FIGURE 3: Specimens being evaluated for compressive and flexural strength. (a) Universal Testing Machine; (b) Sample tested for compressive strength; (c and d) Samples tested for flexural strength

Results And Discussion

Results

Flexural strength: The 5% E-glass fiber group achieved a mean flexural strength of 82.94 ± 4.64 MPa, significantly higher than the 3% fiber group (75.52 ± 6.70 MPa) (Welch's t(16.02) = -2.88, p = 0.011; Cohen's d = -1.29). The 5% fiber group performed comparably to Tetric N Ceram (88.63 ± 28.72 MPa) and Charisma Smile (84.26 ± 18.47 MPa). ANOVA across all four groups also revealed a significant effect (F(3,36) = 5.75, p = 0.0026). However, Tukey's post hoc test did not detect significant pairwise differences (all p > 0.05), suggesting that although overall group variation was significant, individual comparisons were not strong enough after adjustment (Tables *3* and 4).

Compressive strength: The 5 wt% E-glass fiber group demonstrated a mean compressive strength of 124.31 ± 27.69 MPa, which was higher than Brilliant NG (54.20 ± 8.62 MPa) and comparable to Tetric N Ceram (137.65 ± 78.63 MPa), but not significantly different from the 3 wt% fiber group (101.97 ± 22.50 MPa) (Welch's (t(17.28) = -1.98, p = 0.064; Cohen's d = -0.89). One-way ANOVA demonstrated a significant difference among all four groups (F(3,36) = 16.38, p < 0.001). Tukey's post hoc analysis indicated that Brilliant NG exhibited significantly lower compressive strength compared to Group D (5% fiber, p = 0.006) and Tetric N Cream (p = 0.011). No other pairwise comparisons reached statistical significance (Tables *5* and 6).

The 5% experimental groups exceeded the ISO 4049 minimum flexural strength requirement for posterior composites (≥80 MPa); however, the 3% E-glass fiber group did not meet the minimum flexural strength requirement of 80 MPa specified by ISO 4049 for restorative composites. While neither fiber-reinforced composite reached the 250 MPa compressive strength benchmark often cited for posterior restorative materials, the observed improvements support the mechanical viability of optimized fiber reinforcement in BisEMA-based systems. Table *7* summarizes the pairwise statistical comparisons for flexural and compressive strength between groups. Figure *4* shows a graph representing the flexural and compressive strength values of the experimental composite groups compared with commercial materials.

Group No.	% of Glass Fiber	Flexural Strength – Mean and SD
A	3%	75.52 ± 6.70
B	5%	82.94 ± 4.64

TABLE 3: Mean and standard deviation of flexural strength for experimental composites with different E-glass fiber content

S. No.	Brand Name	Manufacturer	Flexural Strength – Mean and SD
1	Tetric N Ceram (BisGMA + UDMA)	3MESPE - USA	88.63 ± 28.77
2	Charisma Smile (BisGMA)	Ivoclar	84.26 ± 18.47

TABLE 4: Mean and standard deviation of flexural strength for commercial composite brands

Group No.	% of Glass Fiber	Compressive Strength – Mean and SD
C	3%	101.97 ± 22.50
D	5%	124.31 ± 27.69

TABLE 5: Mean and standard deviation of compressive strength for experimental composites with different E-glass fiber content

S. No.	Brand Name	Manufacturer	Compressive Strength – Mean and SD
1	Tetric N Ceram (BisGMA + UDMA)	3MESPE - USA	137.65 ± 78.63
2	Brilliant NG (BisGMA + TEGDMA)	Waldent	54.20 ± 8.62

TABLE 6: Mean and standard deviation of compressive strength for commercial composite brands

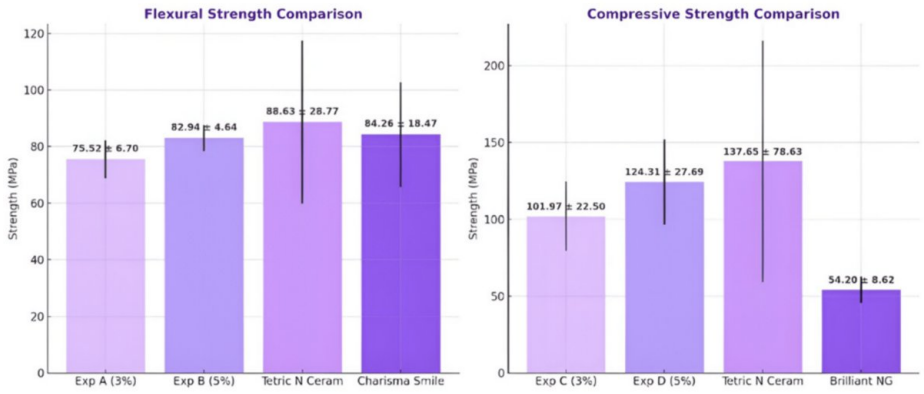

FIGURE 4: Bar graph representing flexural and compressive strength values of experimental and control groups

Group/Material	Mean ± SD	Property	Key Statistical Findings
C (3% fiber)	101.97 ± 22.50	Compressive	Not significantly different from D (p = 0.064)
D (5% fiber)	124.31 ± 27.69	Compressive	Higher than Group C, NS (p = 0.064)
Tetric N Cream	137.65 ± 78.63	Compressive	Significantly more than Brilliant NG (p = 0.011)
Brilliant NG	54.20 ± 8.62	Compressive	Significantly less than group D and Tetric N (p = 0.006, 0.011)
A (3% fiber)	75.52 ± 6.70	Flexural	Significantly less than group B (p = 0.011)
B (5% fiber)	82.94 ± 4.64	Flexural	Significantly more than group A (p = 0.011)
Tetric N Ceram	88.63 ± 28.77	Flexural	No pairwise differences (NS)
Charisma Smile	84.26 ± 18.47	Flexural	No pairwise differences (NS)

TABLE 7: Summary of pairwise statistical comparisons for flexural and compressive strength between groups

Discussion

The present study evaluated the influence of E-glass fiber reinforcement at 3% and 5% by weight on the flexural and compressive strengths of an experimental BisEMA/TEGDMA composite resin, with three commercial restorative materials serving as controls. The findings showed that 5% fiber loading significantly improved flexural strength compared to 3% fiber loading, achieving values comparable to high-strength commercial composites such as Tetric N Ceram and Charisma Smile. While compressive strength also increased with 5% fiber loading, the improvement did not reach statistical significance when compared to the 3% group, although the effect size indicated a substantial mechanical benefit.

According to Garoushi et al., the improvement in flexural strength with higher fiber content can be attributed to the fiber's crack-bridging and energy-dissipating mechanisms during loading. E-glass fibers act as stress-transferring elements, redirecting tensile forces from the weaker resin matrix into the stiffer fibers, thereby delaying crack initiation and propagation [18]. Similar findings were reported by Lassila et al., who showed that short E-glass fibers enhance the flexural strength of composite resins by arresting microcrack growth and improving fatigue resistance. This reinforcement effect is optimized when fibers exceed the critical length for stress transfer, reported to be approximately 0.5-1.5 mm for E-glass in dental composites [19]. In this study, fibers of 1.5 mm length were used, which are at the upper limit of the critical length range, thereby ensuring effective load transfer and consistent with earlier reports demonstrating superior mechanical performance when fibers approach or exceed this threshold.

The absence of a statistically significant difference in compressive strength between 3% and 5% fiber groups aligns with earlier findings of Hashim et al., suggesting that fiber reinforcement contributes more to tensile and flexural performance than to compressive resistance [20]. A study done by Garoushi et al. concluded that under compressive loading, the resin matrix plays a dominant role in deformation, and the stiff fibers may act as stress concentrators if not perfectly aligned, potentially limiting their strengthening effect [21]. Nevertheless, the observed increase in mean compressive strength for the 5% group, along with the large effect size, suggests a clinically relevant improvement that might be more pronounced under fatigue or impact loading conditions.

Comparisons with commercial controls provide additional insights. The 5% fiber group achieved flexural strengths comparable to Tetric N Ceram and Charisma Smile, both microhybrid composites known for high filler load and robust mechanical profiles. This equivalence in flexural performance, despite the experimental composite's relatively lower inorganic filler content, underscores the efficiency of fiber reinforcement in enhancing structural resilience. In compressive strength, the fiber-reinforced groups outperformed Brilliant NG, a nanohybrid composite, which is consistent with literature indicating that nanofilled and nanohybrid composites may underperform in bulk mechanical tests compared to microhybrids due to differences in filler packing density and resin-filler interface characteristics [22].

From a materials science perspective, BisEMA offers several advantages over BisGMA- and UDMA-based systems, including lower water sorption, reduced solubility, and lower polymerization shrinkage stress. However, its lower viscosity can reduce the polymer's cross-link density, potentially compromising mechanical strength. The results of the present study suggest that E-glass fiber reinforcement is a viable strategy to offset this inherent limitation, producing mechanical performance that meets or exceeds ISO 4049 flexural requirements for posterior composites (ISO 4049:2019). The fact that 5% fiber-reinforced

group exceeded the ISO flexural threshold of ⩾80 MPa indicates suitability for high-load clinical applications [23].

These findings are consistent with earlier studies where short E-glass fibers improved fracture toughness, fatigue resistance, and load-bearing capacity of resin composites. Study done by Lassila et al. demonstrated that incorporating 1.5 mm fibers into composite matrices significantly enhanced flexural strength, while Garoushi et al. reported improvements in load-bearing capacity and crack propagation resistance. The present results reinforce these observations, while extending them to BisEMA-based systems, which have been less extensively studied in the context of fiber reinforcement [19,21].

The clinical implications are noteworthy, fiber reinforcement in BisEMA-based composites could allow clinicians to utilize resin materials in high-stress posterior situations where conventional composites might be at greater risk of failure. This could be particularly advantageous in cases involving large MOD cavities or replacement of amalgam restorations, where high fracture resistance is critical. Moreover, the reduced water sorption and improved biocompatibility of BisEMA-based systems may further enhance restoration longevity in the oral environment [24].

However, several factors warrant consideration. Fiber orientation within the matrix is known to influence reinforcement efficacy, with random distribution offering isotropic reinforcement but potentially less effect than unidirectional alignment in specific stress directions. In the present study, fibers were randomly distributed, which is clinically relevant but may underestimate the maximal mechanical benefit achievable with optimized orientation. Additionally, increasing fiber content beyond 5% could further enhance properties but may compromise handling, polishability, and esthetics, as reported in earlier investigations [25].

The results of this study provide compelling evidence that 5% E-glass fiber reinforcement can produce BisEMA/TEGDMA composites with mechanical properties comparable to or exceeding those of established commercial materials in flexural testing, with clinically relevant gains in compressive strength. These findings support further development and optimization of fiber-reinforced BisEMA-based composites for posterior restorations.

Conclusions

The present study demonstrated that incorporation of short glass fibers into composite resin influences its mechanical properties, with 5% fiber reinforcement producing a statistically significant improvement in flexural strength compared to 3%, while compressive strength showed a non-significant upward trend. Among the tested restorative materials, Tetric N Ceram/Cream exhibited superior strength values, whereas Brilliant NG consistently demonstrated lower performance. These findings suggest that higher fiber loading may enhance the ability of composites to resist bending stresses and potentially improve their clinical durability in stress-bearing restorations, core build-ups, and cases requiring reinforcement against fracture. Although in-vitro results provide important insight, clinical performance is multifactorial; therefore, further in-vivo and long-term studies are warranted to confirm the applicability of fiber-reinforced composites in routine restorative dentistry.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Concept and design: Mukul Saini, Niharika N, M Shahid

Acquisition, analysis, or interpretation of data: Mukul Saini, Niharika N, Pushpanjali Krishnappa, Nithin Shetty, Nisarga Nayak TR, Prajwal GC, M Shahid

Drafting of the manuscript: Mukul Saini, Niharika N, Nisarga Nayak TR, Prajwal GC, M Shahid

Critical review of the manuscript for important intellectual content: Pushpanjali Krishnappa, Nithin Shetty

Supervision: Pushpanjali Krishnappa, Nithin Shetty

Disclosures

Human subjects: All authors have confirmed that this study did not involve human participants or tissue.
Animal subjects: All authors have confirmed that this study did not involve animal subjects or tissue.
Conflicts of interest: In compliance with the ICMJE uniform disclosure form, all authors declare the

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