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Novel hydrogen donors as alternative Co-initiators in model dental resins: A performance analysis

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ABSTRACT

Objective: This study evaluated the influence of novel co-initiators on the chemical and physical properties of model dental resins at varying initiator-to-co-initiator ratios.
Methods: A comonomer blend consisting of 50 wt% bis-GMA, 25 wt% TEGDMA, and 25 wt% HEMA was prepared, incorporating 0.5 wt% camphorquinone (CQ) and 0.5 wt% bis(4-methylphenyl)iodonium hexafluorophosphate (IOD). New co-initiators (HD4, HD1, and MHPTm) were tested against standard tertiary amines (DMAEMA and EDAB) at initiator-to-co-initiator ratios of 1:1 and 1:2, resulting in 10 distinct formulations. The properties analyzed included degree of conversion (DC), rate of polymerization (RP), flexural strength (FS), flexural modulus (*E*), water sorption (W*sp*), and solubility (W*sol*). Data for DC, FS, E, and W*sp* were analyzed using two-way ANOVA and Tukey's test ($\alpha = 0.05$), and Sol was analyzed with Kruskal-Wallis and Dunn tests ($\alpha = 0.05$).
Results: For the 1:1 ratio, DMAEMA, EDAB, HD4 and MHPTm exhibited statistically higher DC values compared to HD1, while DMAEMA and EDAB showed the highest DC at the 1:2 ratio. Similar trends were noted for RP, FS, and E. For W*sp*, DMAEMA and HD4 showed the statistically highest levels, whereas HD4 and HD1 had the highest Sol in the 1:1 formulation. Overall, the 1:2 initiator-to-co-initiator ratio improved the properties of the novel hydrogen donors tested compared to 1:1 ratio.
Conclusions: The novel co-initiators demonstrated promising properties for model resins compared to standard references, with the 1:2 ratio yielding the most favorable results for these alternative hydrogen donors.

1. Introduction

The camphorquinone (CQ)/amine system, classified as a type II photoinitiator system, is the most widely used in resin-based dental materials. Among most commonly used co-initiators are amines such as ethyldimethylaminobenzoate (EDAB) and 2-(dimethylamino)ethyl methacrylate (DMAEMA) (Andrade et al., 2016; de Oliveira et al., 2015). Polymerization is triggered by a hydrogen abstraction reaction involving CQ in its triplet state and an amine, which acts as the hydrogen donor. This reaction is subsequently followed by electron and proton transfer, resulting in the formation of initiating amino-alkyl radicals, which are highly reactive species capable of efficiently initiating polymerization processes (Azad et al., 2018; Dressano et al., 2020; Guimaraes et al., 2014; Schneider et al., 2008).

Despite their efficiency and utility, there is increasing concern regarding the toxicity of the tertiary amines used in dental resins. According to the European Chemicals Agency (ECHA), EDAB is harmful if ingested and may also pose risks to fertility or to unborn child (Sprick

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et al., 2020a, 2021). Although these amines are still widely used in dental resins, the development of alternative systems is imperative to enhance the safety of materials employed in dental procedures, particularly those applied in restorative treatments.

To develop dental resin systems without amines, previous studies have explored amine-free systems based on urethane dimethacrylate (UDMA) (Salvador et al., 2021, 2022). In such systems, the high concentration of the alkyl urethane moiety (-NH-CH2) within the monomer, combined with its favorable oxidation potential, enables efficiently interactions with the triplet-excited state of CQ (^{3}CQ also noted *CQ). This interaction facilitates electron transfer, proton transfer, or hydrogen abstraction reactions, thereby promoting the formation of free radicals necessary for polymerization (Asmusen et al., 2009; Salvador et al., 2021). However, while promising, the use of UDMA-based amine-free systems imposes limitations on resin composition. A significant amount of UDMA is required to drive the polymerization reaction, limiting the incorporation of other important crosslinking monomers, such as Bisphenol-A glycidyl dimethacrylate (BisGMA) (Asmusen et al., 2009).

Various studies have investigated new co-initiators as alternatives to the commonly used EDAB and DMAEMA, aiming to identify safer and more efficient molecules (Kirschner et al., 2020; Sprick et al., 2020a, 2021). These new compounds were synthesized and combined with an iodonium salt (IOD), forming a ternary system consisting of CQ, a co-initiator, and IOD (Albuquerque et al., 2015; Cook and Chen, 2015; Sprick et al., 2020a, 2021). The use of IOD in dental resin systems has been extensively studied by different researchers, demonstrating its effectiveness in enhancing system reactivity. This results in an increased rate and monomer conversion, improved mechanical properties, and reduced water sorption (W*sp*) and solubility (W*sol*) of the materials (Dressano et al., 2016; Leite et al., 2018; Lima et al., 2019; Oxman et al., 2005; Palialol et al., 2021; Verzola et al., 2020). In addition, the new co-initiators showed similar or improved cytocompatibility with dental pulp stem cells, indicating that these new hydrogen donors are safe for use in dental materials (Lima et al., 2024). This is particularly relevant for dental adhesives, which can diffuse through dentinal tubules and reach the dental pulp.

Although previous studies have shown that the new hydrogen donors exhibit similar efficacy to the traditionally used EDAB in terms of resin degree of conversion, while offering improved bleaching properties (Sprick et al., 2020a, 2021), the influence of these co-initiators on critical physical and chemical properties relevant to the performance of dental materials remains unknown. Therefore, this study evaluated the impact of new co-initiators on a model dental resin formulation, focusing on the effects of varying CQ initiator-to-co-initiator ratios. The study aimed to assess these new co-initiators' influence on the degree of conversion (DC), rate of polymerization (RP), flexural strength (FS), flexural modulus (*E*), W*sp*, and W*sol*. The hypotheses tested were: (1) the new co-initiators would promote properties comparable to those observed in dental resin materials using benchmark co-initiators, and (2) both initiator:co-initiator ratios tested would yield similar chemical and physical properties.

2. Materials and methods

2.1. Syntheses of HD4, HD1 and MHPTm

The syntheses of new co-initiators were performed as described in previous studies (Sprick et al., 2020a, 2020b):

N-(2-[1,3-benzodioxol-5-yl] ethyl)-2-methylprop-2-enamide (HD1) was prepared according to the general procedure, starting from 3,4-methylenedioxyphenethylamine hydrochloride (Sigma–Aldrich, Merck KGaA, Darmstadt, Germany) (1.00 g, 4.96 mmol), methacrylic anhydride (Sigma–Aldrich, Merck KGaA, Darmstadt, Germany) (1.18 mL, 7.93 mmol) and triethylamine (Sigma–Aldrich, Merck KGaA, Darmstadt, Germany) (1.10 mL, 7.93 mmol). After purification, the product was obtained as a colorless oil (1.06 g, 92 %). 1H NMR (300 MHz, CDCl3) δ 6.73–6.60 (m, 3H), 5.90 (s, 2H), 5,80 (br s, 1H), 5.62 (s, 1H), 5.29 (s, 1H), 3.49 (q, J = 6.6, 6.5 Hz, 2H), 2.74 (t, J = 6.5 Hz, 2H), 1.90 (s, 3H).

N-(1,3-benzodioxol-5-ylmethyl)-2-methylprop-2-enamide (HD4) was prepared using piperonylamine (Sigma–Aldrich, Merck KGaA, Darmstadt, Germany) (1.00 g, 6.62 mmol), methacrylic anhydride (Sigma–Aldrich, Merck KGaA, Darmstadt, Germany) (1.58 mL, 10.59 mmol) and triethylamine (Sigma–Aldrich, Merck KGaA, Darmstadt, Germany) (1.47 mL, 10.59 mmol). After purification, the product was obtained as a colorless oil (1.32 g, 96 %). 1H NMR (300 MHz, CDCl3) δ 6.77–6.73 (m, 3H), 6.27 (br s, 1H), 5.92 (s, 2H), 5.70 (s, 1H), 5.33 (s, 1H), 4.36 (d, J = 6.3 Hz, 2H), 1.96 (s, 3H).

MHPTm: A solution of MHPT (1.00 g, 6.05 mmol, 1 equiv) in CHCl3 (Sigma–Aldrich, Merck KGaA, Darmstadt, Germany) (10 mL) was stirred and cooled to 0 °C. Methacrylic anhydride (Sigma–Aldrich, Merck KGaA, Darmstadt, Germany) (1.44 mL, 9.68 mmol, 1.6 equiv) and Et3N (Sigma–Aldrich, Merck KGaA, Darmstadt, Germany) (1.34 mL, 9.68 mmol, 1.6 equiv) were successively added dropwise at 0 °C. The mixture was allowed to warm up to room temperature and stirred for another 24 h. The organic phase was successively washed with distilled water (30 mL), 1 N HCl (Sigma–Aldrich, Merck KGaA, Darmstadt, Germany) (20 mL), and 1 N NaHCO3 (Sigma–Aldrich, Merck KGaA, Darmstadt, Germany) (20 mL), dried with anhydrous MgSO4 (Sigma–Aldrich, Merck KGaA, Darmstadt, Germany), filtered, and concentrated under vacuum. The crude reaction mixture was purified by flash chromatography on silica gel (AcOEt/hexane: 1:3) to afford the product as a pale orange oil (1.29 g, 91 % isolated yield). 1H NMR (300 MHz, CDCl3) δ 7.09 (d, J = 8.7 Hz, 2H), 6.73 (d, J = 8.7 Hz, 2H), 6.12 (d, J = 3.8 Hz, 1H), 5.58 (d, J = 3.8 Hz, 1H), 4.36 (t, J = 6.2 Hz, 2H), 3.65 (t, J = 6.2 Hz, 2H), 3.01 (s, 3H), 2.30 (s, 3H), 1.97 (s, 3H).

2.2. Resin preparation

A model resin formulation was prepared using 50 wt% bisphenol A-glycidyl methacrylate (BisGMA, Esstech Inc., Essington, PA, USA), 25 wt % triethylene glycol dimethacrylate (TEGDMA, Esstech Inc.), and 25 wt % hydroxyethyl methacrylate (HEMA, Esstech Inc.). Camphorquinone (CQ, Esstech Inc.) at 0.5 wt% and bis(4-methylphenyl)iodonium hexafluorophosphate (IOD, Sigma–Aldrich Inc., St. Louis, MO, USA) at 0.5 wt % were incorporated as part of the photoinitiator system. The co-initiators 2-(dimethylamino)ethyl methacrylate (DMAEMA, Sigma–Aldrich Inc.) and ethyldimethylaminobenzoate (EDAB, Sigma–Aldrich Inc.) were used as reference compounds. The molecular structures of the initiator and co-initiators used in this study are shown in Fig. 1.

The initiator-to-co-initiator ratios for all evaluated hydrogen donors were 1:1 and 1:2, based on the weight percentage of each tested co-initiator, resulting in a total of 10 groups. Table 1 presents the molar concentrations (g/mol) calculated according to the molecular weight (MW) and weight percentage (% wt) of the different co-initiators: DMAEMA (MW: 157 g/mol), EDAB (MW: 193 g/mol), HD4 (MW: 219 g/mol), HD1 (MW: 233 g/mol), and MHPTm (MW: 233.31 g/mol).

2.3. Polymerization kinetics

Real-time polymerization kinetics were monitored using Fourier transform infrared spectroscopy with attenuated total reflectance (ATR) (FTIR, IS50, Thermo Scientific, Pittsburgh, PA, USA). A reproducible specimen dimension was achieved by securing a silicone mold (5 mm diameter, 1 mm thickness) onto the ATR plate (Thermo Fisher, Smart MIRacle Diamond ATR, Waltham, Massachusetts, USA), ensuring concentric alignment with the ATR diamond. The mold was then filled with the each resin blend (n = 3), and a glass slide (~0.1 mm thick) was placed on top of the resin. For all evaluations, the model dental resins were light cured using a broad spectrum of wavelength (385–515 nm) light-curing unit (LCU; LED Bluephase G2, Ivoclar Vivadent AG, Schaan, Liechtenstein), with mean radiant emittance (tip irradiance) of 1200

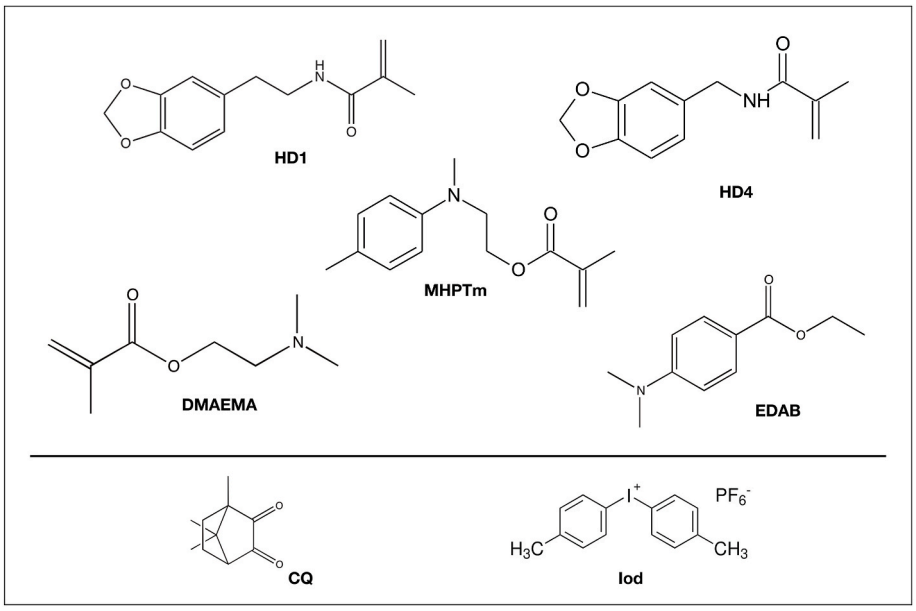

Fig. 1. Molecular structure of the hydrogen donors co-initiators (DMAEMA, EDAB, HD4, HD1, MHPTm) and initiators (CQ, IOD) used in the present study.

Table 1
Molar amount of co-Initiators per gram of resin based on molecular weight and weight percentage at different initiator-to-co-initiator ratios.

Co-initiators	Co-initiator concentration	
	0.5 % wt (1:1 ratio)	1 % wt (1:2 ratio)
DMAEMA	3.18 e−05	6.37 e−05
EDAB	2.59 e−05	5.18 e−05
HD4	2.28 e−05	4.57 e−05
HD1	2.15 e−05	4.29 e−05
MHPTm	2.14 e−05	4.29 e−05

mW/cm^2, exposure time of 40 s at a 0 mm distance (light curing unit tip touching the glass slide), resulting in 48 J/cm^2 radiant exposure.

The aliphatic (1638 cm^{-1}) and aromatic (1608 cm^{-1}) C=C absorption peaks were followed over 120 s, at Oi3 scans averaged per spectrum, with 16 cm^{-1} resolution. The DC was calculated according to Eq. (1) (Rueggeberg et al., 1990) and the rate of polymerization (RP) was calculated as the derivative of the DC versus time.

$$Conversion\ \% = 1 - \frac{aliphatic/isosbestic\ (peak\ areas\ of\ polymer)}{aromatic/isosbestic\ (peak\ areas\ of\ monomer)}\ x100 \quad \text{(Equation 1)}$$

2.4. Flexural strength (FS) and modulus (E)

FS and *E* were assessed using a three-point bending test (n = 12). Bar-shaped specimens (25 mm in length, 2 mm in width, and 2 mm in height) were fabricated using a stainless-steel mold (Odeme Dental Research, Luzerna, SC, Brazil). The mold was placed on a glass plate and filled with the prepared resin formulations. A glass slide (0.1 mm thick) was positioned on top of the resin prior to curing.

The specimens were photopolymerized with the LCU mentioned above, with the tip positioned centrally and aligned flat along the axis of the bar, using five successive overlapping irradiations (5 × 40 s) starting from the center of the specimen. After preparation, the specimens were stored dry in the dark at 37 °C for 24 h.

The dimensions of the specimens were measured immediately prior to testing using a digital caliper (Mitutoyo, Tokyo, Japan) with an accuracy of 0.01 mm. Three-point bending tests were conducted using a universal testing machine (2000RK, Kratos, São Paulo, Brazil) at a crosshead speed of 1 mm/min. The distance between the supports was set at 20 mm. FS was calculated according to Equation (2):

$$FS = \frac{3FI}{2bh^2} \quad \text{(Equation 2)}$$

"F" = maximum load (Newtons) required to fracture the specimen.
"l" = distance between supports (20 mm).
"b" = average specimen width and "h" the average thickness.

E was calculated from the linear portion of the stress-strain curve, using Equation (3):

$$E = \frac{\Delta F}{\Delta Y}\ x\ \frac{I^3}{4bh^3} \quad \text{(Equation 3)}$$

ΔF/ΔY = force change (ΔF) per unit changes in deflection (ΔY) at the center of the specimen.
L = distance between supports (20 mm);
b = average specimen width
h = average thickness.

2.5. Water sorption (Wsp) and solubility (Wsol)

Silicone molds were employed to prepare discs (n = 5) measuring 4 mm in diameter and 2 mm in thickness. After transferring the resins into the molds, a Mylar strip was placed over the upper surface. Following polymerization with the LCU mentioned above for 40 s, the specimens were stored in plastic tubes at 37 °C within a desiccator.

The samples were weighed daily during the drying period using an analytical balance (Discovery DV215CD, Ohaus Corporation, Pine Brook, NJ, USA) until a constant weight was achieved (variation less than ± 0.1 mg for three consecutive measurements). Once stabilization of the weight was confirmed, the diameter and thickness of the samples were measured to calculate their volume (in mm^3). Following the determination of the initial weight (m1), the samples were individually stored in plastic tubes containing 1.5 mL of distilled water and incubated at 37 °C for 7 days. After this period, the samples were removed from the incubator, gently dried with absorbent paper, and weighed to determine the mass after immersion in water (m2). After obtaining m2, the samples were placed in a desiccator at 37 °C and weighed daily until a constant weight was achieved (denoted as m3). The calculations for W*sp* and W*sol* were performed according to the guidelines specified in ISO 4049/2000.

W*sp* was calculated in $\mu g/mm^3$ using the following equation:

$$Wsp = ((m2 - m3))/V \quad \text{(Equation 4)}$$

m2 = mass after immersion in distilled water in μg
m3 = mass after the second drying cycle in μg.
V = volume of the m1 sample in mm^3.
The W*sol* was calculated in mg/mm3, by the following equation:

$$Wsol = ((m1 - m3))/V \quad \text{(Equation 5)}$$

where m1 is initial weight before immersion in distilled water in μg.

2.6. Water uptake

The water uptake of the resins was evaluated after obtaining the initial mass (m1). Sequential weight measurements were conducted following immersion in water at the time intervals of 2 h, 4 h, 6 h, 8 h, 10 h, 12 h, 24 h, 48 h, 72 h, and 7 days. The initial mass, determined after the first desiccation process (m1), was used to calculate the changes in mass at each specified time point. The mass variations were plotted against storage time to determine the kinetics of water absorption over the entire storage period.

2.7. Statistical analysis

Data were analyzed by Shapiro Wilk test to evaluate the normality of the obtained data ($p \leq 0.05$). The results of each test were analyzed by two-way ANOVA, considering the factors "co-initiator" and "initiator: co-initiator ratio" as main factors. For comparison among groups in all evaluations, Tukey's post-hoc test was performed. For the W*sol* results, as the assumptions required for performing ANOVA were not met, a non-parametric analysis was conducted using the Kruskal-Wallis test followed by Dunn's post-hoc test was used to compare the different co-initiators within the same ratio. Mann-Whitney test was used to compare the ratios within the same resin. All analysis was evaluated at 5 % significance level.

3. Results

3.1. Polymerization kinetics

For both DC and rate of polymerization, the two factors significantly influenced the results and demonstrated significant interaction between each other ($p < 0.001$). The DC for resins with an initiator:co-initiator ratio of 1:1 was similar across all formulations, except for the resin containing HD1, which exhibited the lowest DC (Table 2, Figs. 2 and 3). At the 1:2 ratio, the resin containing DMAEMA showed the highest DC, followed by MHPTm and EDAB. HD4 and HD1 showed a slight but statistically significant reduction in DC. When comparing the different ratios, DMAEMA and MHPTm displayed significantly higher DC at the 1:2 ratio than at 1:1.

The RP was highest for resins containing DMAEMA and EDAB at the 1:1 ratio. HD4 and HD1 resulted in the lowest RP, while resins containing EDAB and MHPTm showed intermediate values. For 1:2 Ratio, DMAEMA exhibited the highest RP ($p < 0.04$). EDAB and MHPTm presented intermediate RP. HD1 and HD4 showed the lowest RP, cut HD1 was significantly lower than HD4. When comparing the two ratios, resins with HD4, and HD1 exhibited a higher RP at the 1:2 ratio compared to the 1:1 ratio.

3.2. Flexural strength and modulus

For both FS and *E*, the interactions between the factors were significant ($p < 0.0001$ for both). At the initiator:co-initiator ratio of 1:1, the co-initiators DMAEMA, EDAB, and MHPTm yielded the highest FS (Fig. 4). The FS in descending order was as follows: HD1 > HD4 ($p < 0.05$). In contrast, at the 1:2 ratio, EDAB demonstrated the highest FS, while MHPTm, HD4, and HD1 showed statistically similar results, which differed from EDAB. DMAEMA promoted FS similar to all resins tested.

When comparing the ratios, the resins containing HD4, and HD1 showed increased FS when using the 1:2 ratio. Conversely, MHPTm resulted in reduced FS at the 1:2 ratio compared to the 1:1 ratio.

For *E*, the results mirrored those observed for FS, with DMAEMA, EDAB, and MHPTm exhibiting the highest *E* values (Fig. 5). In descending order, the *E* was ranked as follows: HD1 > HD4 ($p < 0.05$) at the 1:1 ratio. At the 1:2 ratio, EDAB yielded the highest *E*, while DMAEMA, MHPTm, HD4, and HD1 showed statistically similar results.

Similar to the findings for FS, the resins containing HD4 and HD1 showed increased *E* when using the 1:2 ratio compared to the 1:1 ratio. Additionally, MHPTm resulted in a reduced *E* at the 1:2 initiator:co-initiator ratio compared to the 1:1 ratio.

Table 2
– Degree of conversion of methacrylate functionalities (%) and maximum rate of polymerization (%/s) of the tested resins according to the co-initiator type and ratio.

Degree of Conversion (%)		
Co-Initiator	Initiator:co-initiator ratio	
	1:1	1:2
DMAEMA	73.4 (1.3) A	78. (1.0) A*
EDAB	73.9 (1.3) A	74.3 (0.4) B
HD4	72.6 (0.6) A	70.9 (0.7) C
HD1	68.7 (0.3) B	70.5 (1.0) C
MHPTm	73.0 (1.3) A	75.1 (0.3) B*
Maximum Rate of Polymerization (%/s)		
Co-Initiator	Initiator:co-initiator ratio	
	1:1	1:2
DMAEMA	12.9 (0.5) A	13.8 (0.08) A
EDAB	12.3 (0.2) AB	12.1 (0.2) B
HD4	5.3 (0.4) C	6.7 (0.1) D*
HD1	6.1 (0.7) C	7.9 (0.4) C*
MHPTm	11.4 (0.3) B	11.9 (0.2) B

Different letters indicate statistically significant differences between the resins within the same ratio. An asterisk (*) indicates a statistically significant difference between the ratios within the same resin, according to ANOVA two-way and Tukey test ($\alpha = 0.05$).

3.3. Water sorption

For W*sp*, only the factor "co-initiator" was statistically significant ($p = 0.002$). The factor "ratio" and the interaction between the factors were not significant ($p = 0.290$ and $p = 0.119$, respectively). At the 1:1 ratio, the resins containing DMAEMA and HD4 exhibited the highest WS, followed by the MHPTm resin (Fig. 6). The resins with EDAB and HD1 presented the lowest W*sp*. When the ratio was adjusted to 1:2, all resins displayed comparable W*sp* (see Fig. 7).

3.4. Water uptake

The water uptake analysis revealed that a significant portion of water absorption occurred within the first 24 h, with the samples absorbing approximately 1–1.3 mg of water. Between 24 and 48 h, the rate of water uptake decreased substantially, with an additional absorption of only 0.2–0.4 mg. Following this period, the resins either stabilized in mass or exhibited a slight increase in water content, which persisted until the final evaluation at seven days (168 h).

3.5. Solubility

The non-parametric analysis indicated that the 1:1 ratio was statistically significant ($p < 0.001$). At this ratio, resins containing DMAEMA and EDAB showed the lowest W*sol*, while HD4 exhibited the highest (Fig. 8). The remaining resins presented intermediate W*sol* values. At the

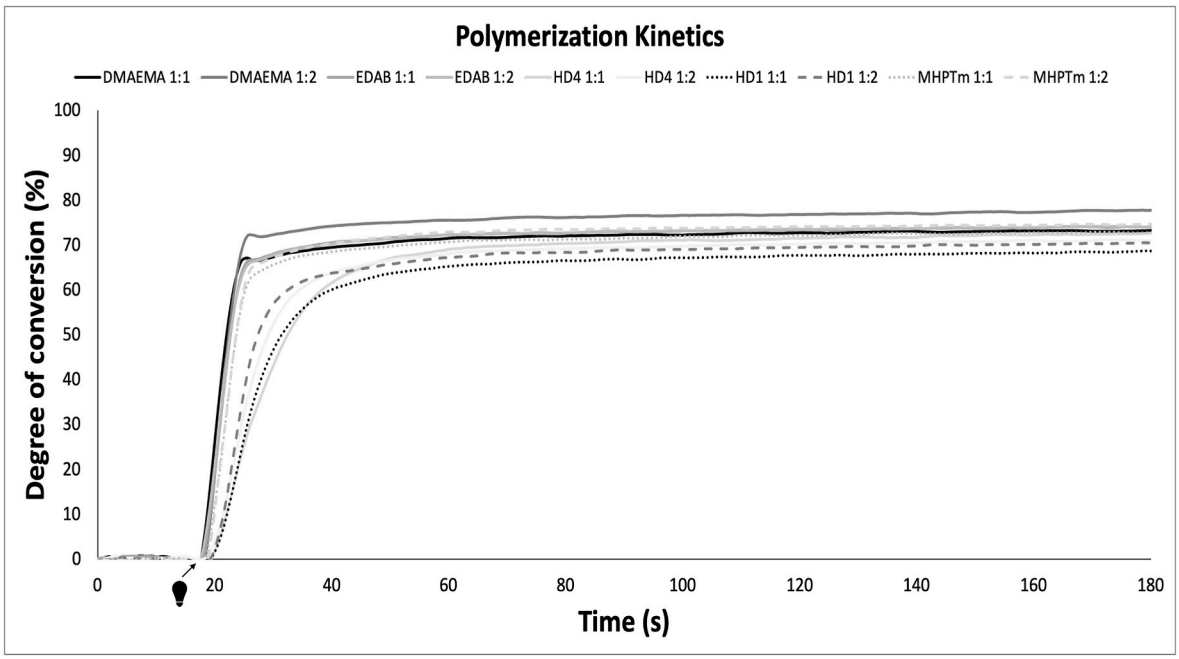

Fig. 2. Real-time degree of conversion (%; n = 5) of the resins. Irradiation begins at the lamp symbol indicated in the graph.

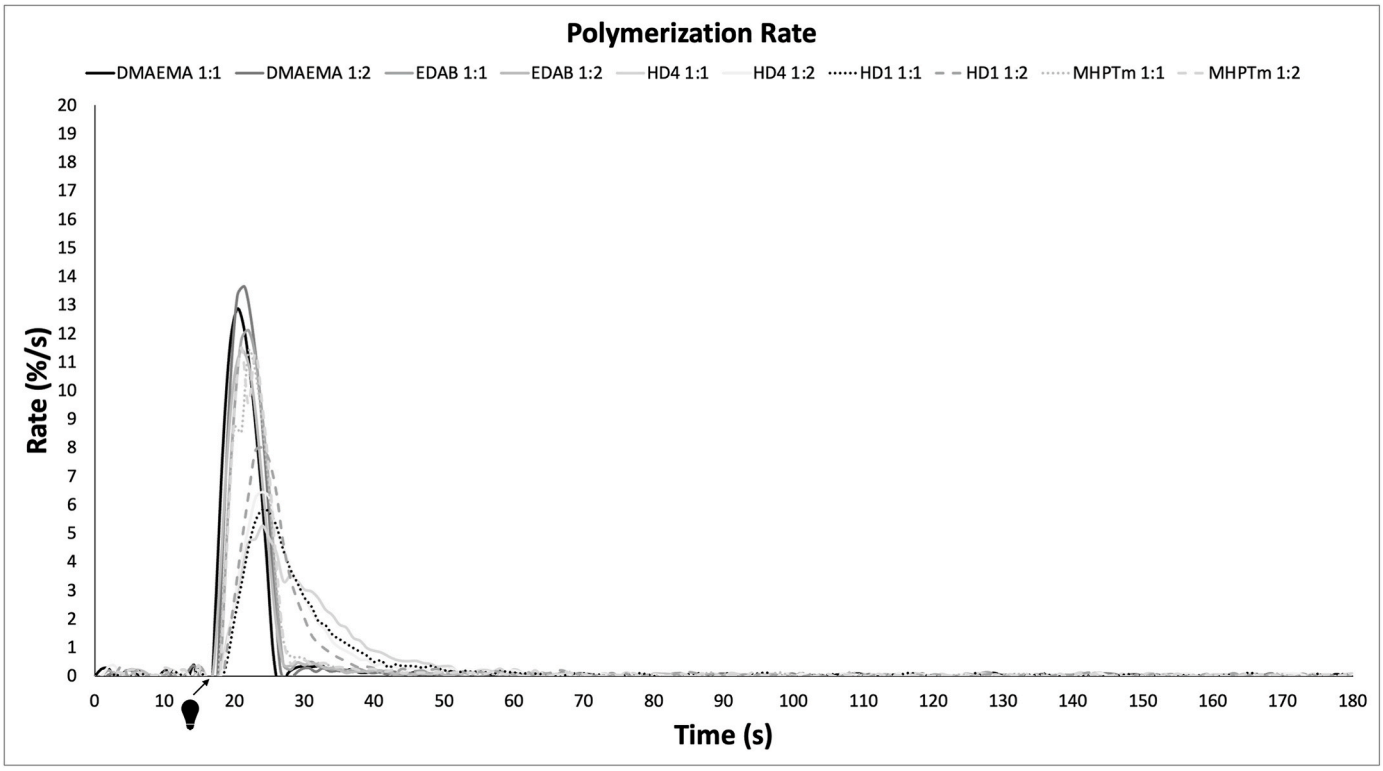

Fig. 3. Polymerization rate (%/s; n = 5) as a function of time of the evaluated resins. Irradiation begins at the lamp symbol indicated in the graph.

1:2 ratio, all resins demonstrated similar W*sol* parameters.

4. Discussion

The search for novel initiator systems is essential for enhancing the polymerization process, particularly under challenging conditions. While current materials achieve good polymerization, certain situations — such as deep cavities, polymerization of resin materials beneath indirect restorations (ceramic and resin), and within root canals — pose difficulties in achieving optimal polymerization due to light attenuation (Al Nahedh et al., 2022; Lim et al., 2024). Furthermore, new molecules may offer improved safety for oral tissues, minimizing adverse effects caused by the exposure of certain chemical compounds to various types of cells (Agostinelli et al., 2023; Lima et al., 2024). This study evaluated new polymerization co-initiators as alternatives to the widely used tertiary amines (DMAEMA and EDAB). The results demonstrated that the

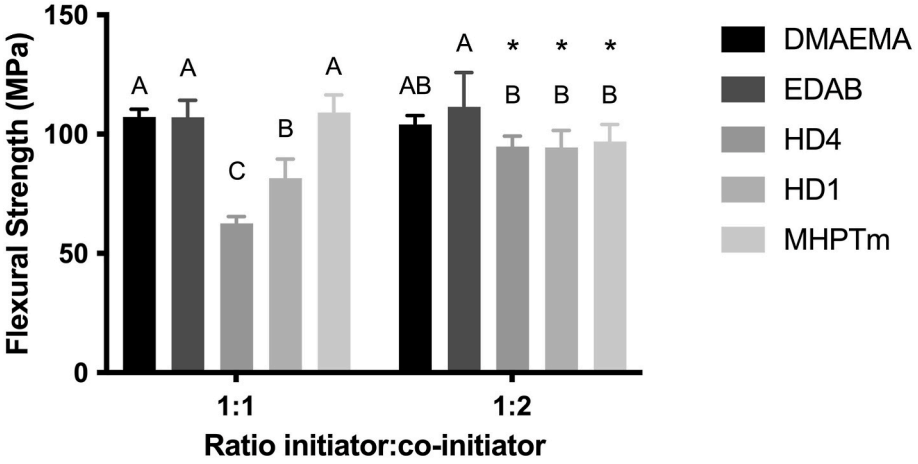

Fig. 4. – Flexural strength (MPa, n = 12) of the resins (n = 12) according to the initiator:co-initiator ratio. Different letters indicate statistically significant differences between the resins within the same ratio. An asterisk (*) indicates a statistically significant difference between the ratios within the same resin, according to ANOVA two-way and Tukey test (α = 0.05).

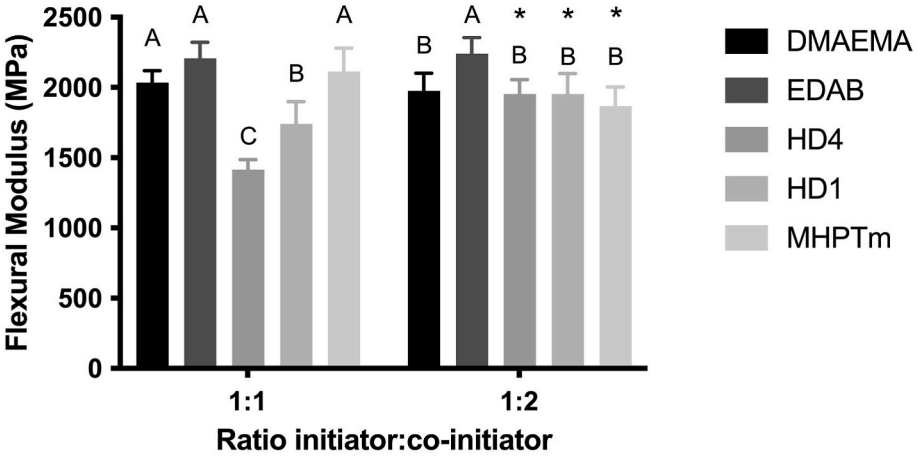

Fig. 5. – Flexural modulus (MPa, n = 12) of the resins according to the initiator:co-initiator ratio. Different letters indicate statistically significant differences between the resins within the same ratio. An asterisk (*) indicates a statistically significant difference between the ratios within the same resin, according to ANOVA two-way and Tukey test (α = 0.05).

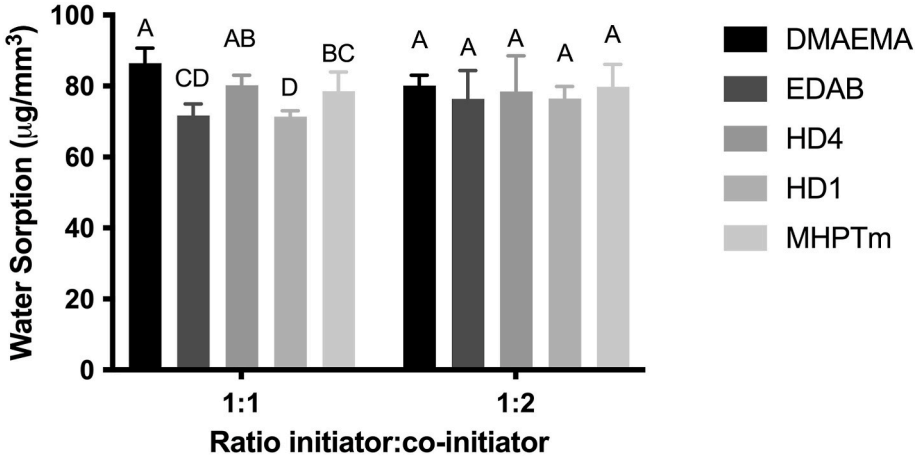

Fig. 6. – Water sorption (μg, n = 5) of the resins according to the initiator:co-initiator ratio. Different letters indicate statistically significant differences between the resins within the same ratio. All groups were similar comparing the ratios within the same resin, according to ANOVA two-way and Tukey test (α = 0.05).

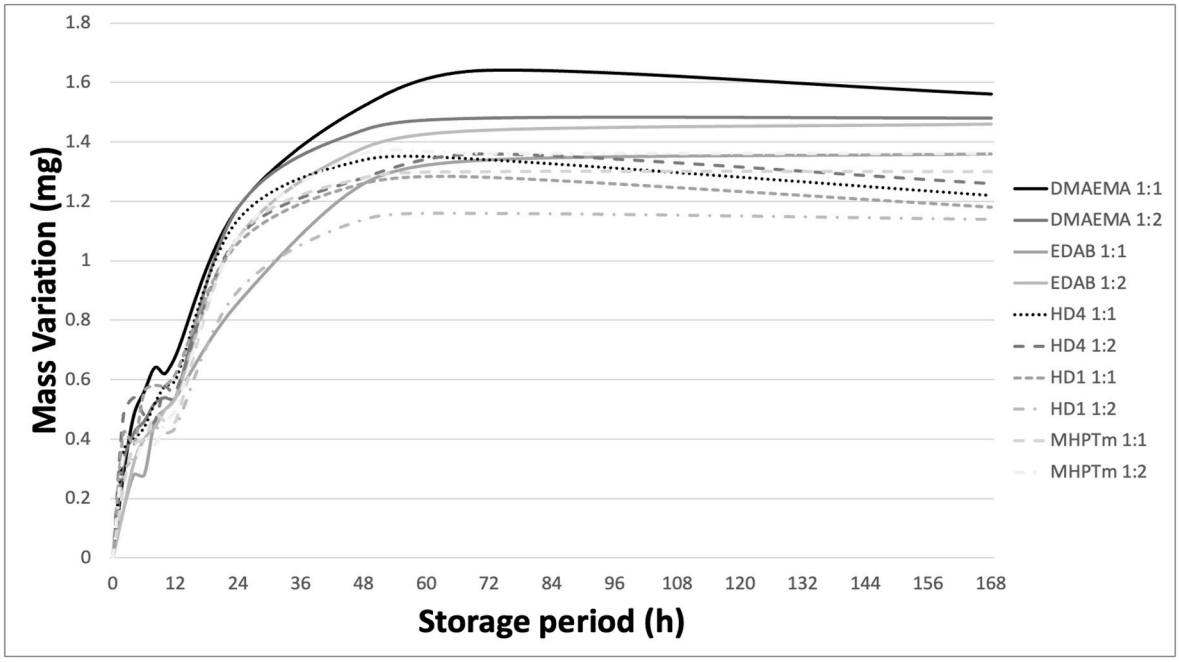

Fig. 7. – Water uptake (mg, n = 5) of the resins tested according to the period of evaluation.

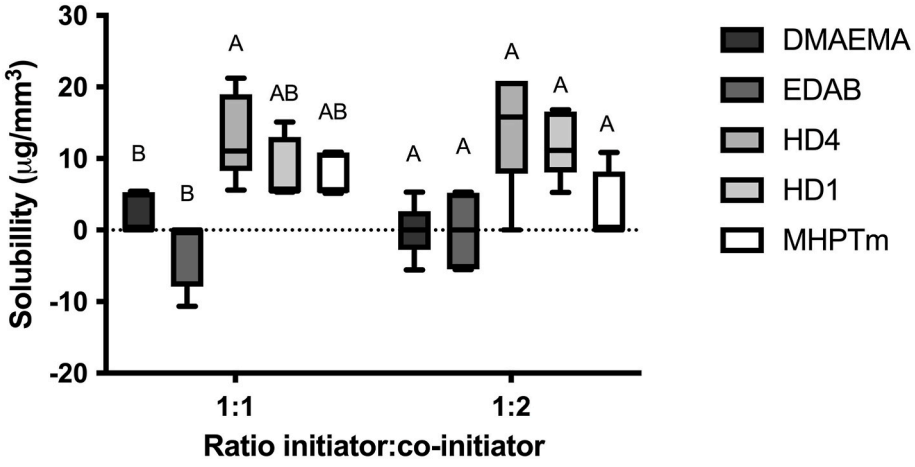

Fig. 8. – Solubility of the resins (μg, n = 5) for the different resins evaluated. Distinct letters indicate statistically significant differences between the resins within each initiator-to-co-initiator ratio. No differences were observed between the ratios within the same resin (Kruskal-Wallis and Dunn tests, α = 0.05).

new hydrogen donors promoted similar or slightly lower properties for the resins evaluated, leading to the rejection of the first hypothesis of the study. However, the findings suggest that the tested molecules could be promising alternatives for use in dental resins, as they produced comparable results to the reference co-initiators, considering using the ratio 1:2.

Table 3
– Calculated C H Bond Dissociation Energies (BDEs) for the labile hydrogen in the new proposed co-initiators calculated at B3LYP/6-31G* level according to the procedure presented in (Sprick et al., 2020a, 2020b).

Co-Initiator	BDE (C-H) (kcal/mol)
DMAEMA	96.7
EDAB	96.2
HD4	96.3
HD1	96.3
MHPTm	95.8

The new hydrogen donors demonstrated a similar or slightly lower DC (approximately 2–3 %) compared to the reference molecules (DMAEMA and EDAB). All hydrogen donors tested had a slightly lower or comparable bond dissociation energy (BDE) relative to the reference molecules, as shown in Table 3. The low C–H BDEs support efficient hydrogen abstraction from the triplet state of CQ, allowing for similar DC. The chemical mechanisms usually correspond to an electron/proton transfer sequence for amine (r1-r2) generating an initiating aminoalkyl radical and not a pure hydrogen abstraction (r3) as observed for HD4 and HD1 (Scheme 1) (Fouassier and Lalevée, 2012). Therefore, the BDE is not the only factor controlling the efficiency of the CQ/co-initiator interaction. EDAB and DMAEMA are well-known for their effectiveness as co-initiators, largely due to their electron-rich nitrogen groups (associated with electron transfer mechanism). The structure of MHPTm, featuring an aromatic amine and an open configuration, seems to replicate some of these beneficial characteristics. Moreover, the presence of aromatic amine structure in MHPTm, as opposed to the configurations of HD1 and HD4, may allow more efficient interactions

$$^3CQ + amine \rightarrow CQ^{\bullet -} + (amine)^{\bullet +} \quad r1$$

$$CQ^{\bullet -} + (amine)^{\bullet +} \rightarrow CQ\text{-}H^{\bullet} + (amine)_{-H}^{\bullet} \quad r2$$

$$^3CQ + H\text{-}D \rightarrow CQ\text{-}H^{\bullet} + D^{\bullet} \quad r3$$

Scheme 1. Expected chemical mechanisms for the formation of the initiating radicals from amine by an electron/proton transfer sequence (r1-r2, for amine based co-initiators) of from pure hydrogen abstraction (r3) from the other H-donors (H–D).

with the CQ excited triplet state through electron-proton transfer mechanism. Indeed, tertiary amine groups, as present in EDAB, DMAEMA, and MHPTm are electron rich and facilitate electron donation to the excited state of CQ. In contrast, nitrogen in acrylamide, such as those in HD1 and HD4, are not good electron donor, thereby making electron transfer to CQ less efficient. The acetal group is the hydrogen donor in HD1 and HD4. The factors described could be a significant factor in enhancing the RP of MHPTm, when comparing to HD4 and HD1, being responsible for the results obtained. Previous studies have reported excellent DC for these new molecules (Sprick et al., 2020a, 2020b, 2021).

Although HD1 and HD4 have molar concentrations comparable to EDAB, their efficiency in electron transfer appears to be lower, which may have contributed to their reduced polymerization performance. In contrast, MHPTm, despite having the lowest molar concentration among the tested co-initiators, demonstrated a high degree of conversion, suggesting that its molecular structure may favor interactions with CQ, optimizing the initiation process. Interestingly, increasing the co-initiator concentration from 1:1 to 1:2 led to different effects depending on the co-initiator type. While DMAEMA showed a statistically significant increase in DC at the 1:2 ratio, EDAB did not follow the same trend, possibly due to saturation effects in electron transfer efficiency. These findings underscore the importance of considering both weight-based and molar fraction perspectives in photoinitiator system formulation, as co-initiator efficacy is influenced not only by its concentration but also by its molecular interactions and electron transfer efficiency in the polymerization mechanism.

Among the co-initiators, HD4 and HD1 exhibited statistically significantly lower RP compared to DMAEMA, EDAB, and MHPTm, which showed high RP values comparable to the reference hydrogen donors used in the present study. However, the lower RP had minimal impact on the final DC of the tested resins. Given that the 1:2 ratio increased the DC for DMAEMA and MHPTm resins, as well as the RP for HD4 and HD1, it can be inferred that the 1:2 ratio is optimal for these co-initiators when used in a ternary initiator system. Also, based on these results, the second hypothesis of this study was rejected.

$^3CQ + amine \rightarrow CQ^{\bullet -} + (amine)^{\bullet +}$ r1

$CQ^{\bullet -} + (amine)^{\bullet +} \rightarrow CQ\text{-}H^{\bullet} + (amine)_{-H}^{\bullet}$ r2

$^3CQ + H\text{-}D \rightarrow CQ\text{-}H^{\bullet} + D^{\bullet}$ r3

In terms of mechanical properties, both FS and *E* exhibited similar trends. MHPTm performed comparably to DMAEMA and EDAB at the 1:1 ratio, achieving the highest FS and *E* among the resins. HD1 followed in FS and *E*, with HD4 exhibiting the lowest values. Since the DC was quite similar across all resins, differences in crosslinking densities, likely influenced by the higher RP of DMAEMA, EDAB, and MHPTm, may account for the observed results. When the ratio was adjusted to 1:2, HD1 and HD4 demonstrated improved performance compared to the 1:1 ratio. The changes in RP may potentially influence network formation, which can directly affect the properties of the tested resins. However, further investigations into resin properties and network formation are necessary to gain a deeper understanding of the influence of the novel co-initiators on methacrylate-based materials. Interestingly, MHPTm showed slightly lower FS and *E* at the 1:2 ratio than at 1:1. It is important to note that the differences in FS and *E* between co-initiators at the 1:2 ratio, as indicated by the statistical analysis, are of low magnitude and should be interpreted with caution, as they may be clinically insignificant in a dental resin.

For W*sp* and water uptake, although statistical analysis indicated some differences, the results across groups with a 1:1 initiator-to-co-initiator ratio were quite similar, with the DMAEMA resin showing the highest W*sp*. The hydrophilic nature of DMAEMA (Guo et al., 2008) may have contributed to the slightly elevated W*sp* observed in this resin, a finding consistent with previous study (Andrade et al., 2016). However, since there is no available data on the hydrophilicity of the other tested co-initiators in comparison to DMAEMA, this factor cannot be definitively identified as the primary cause of the observed results. Conversely, when the initiator-to-co-initiator ratio was changed to 1:2, all resins demonstrated similar levels of W*sp*. The HD4 resin exhibited the highest W*sol*, while DMAEMA and EDAB had the lowest, with the other co-initiators showing intermediate values. Similar to the findings for FS and *E*, variations in crosslinking density likely influenced these outcomes, potentially compromising the W*sol* of the HD4 resin. When the ratio was adjusted to 1:2, all resins displayed comparable W*sol*.

The specimen dimensions used in this study (4 mm diameter, 2 mm thickness) were intentionally modified from the ISO 4049 standard (15 mm diameter, 1 mm thickness) to ensure uniform polymerization. Using larger specimens as preconized by ISO 4049 would have required multiple overlapping light exposures, potentially leading to uneven polymerization and affecting the accuracy of the results. Although reducing the dimensions alters the surface area-to-volume ratio, all sorption and solubility calculations were normalized to volume, ensuring valid comparisons within the study. While direct comparisons with ISO 4049 values are not applicable, the methodological adjustment allowed for a more controlled and reproducible assessment of water sorption and solubility across the tested materials.

Co-initiators play a vital role in resins with Type II initiator systems. For dental resins, where CQ is the most commonly used initiator, identifying new hydrogen donors with high reactivity and improved safety is essential. As described, previous studies have shown that the co-initiators evaluated here exhibit reduced toxicity and minimal impact on pro-inflammatory cytokine release in dental pulp stem cells (Lima et al., 2024). Combining these findings with the results presented in this study suggests that these new co-initiators are promising candidates for future dental resin formulations, offering materials with optimal chemical and mechanical properties, as well as compatibility with dental pulp cells.

5. Conclusions

This manuscript demonstrates that the newly introduced hydrogen donors are viable as co-initiators for resin-based dental materials. The 1:1 initiator:co-initiator ratio was not optimal for the HD1 and HD4 resins. Although these resins exhibited slightly lower properties — such as DC, RP, FS and E – compared to traditional co-initiators. The resins containing MHPTm displayed favorable characteristics, comparable to DMAEMA and EDAB. Notably, the 1:2 initiator:co-initiator ratio yielded the best performance for these novel hydrogen donors.

CRediT authorship contribution statement

Marcos V.O. Salvador: Writing – original draft, Validation, Methodology, Formal analysis. **Matheus Kury:** Writing – review & editing, Validation, Formal analysis, Data curation. **Bruna M. Fronza:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Jean-Pierre Salomon:** Writing – review & editing, Methodology, Investigation. **Jacques Lalevée:** Writing – review & editing, Supervision, Investigation, Conceptualization. **Adriano F. Lima:** Writing – review & editing, Validation, Supervision, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Adriano F. Lima reports financial support was provided by São Paulo Research Foundation (FAPESP) (# 2022/02823-3 and 2023/05652-8). None If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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