Biomaterials Connect
ISSN: 3105-0387
2026, Article ID. 2026.0029, Cite as: https://doi.org/10.69709/BIOMATC.2026.100602

SCIFINITI PUBLISHING

Review Article

OPEN ACCESS

Clinical Effectiveness of Resin Modified Calcium Silicate Cements

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Article History
Received: December 11, 2025 Accepted: June 30, 2026 Published: August 13, 2026

Abstract

This review provides a thorough and critical analysis of the basic properties of resin-modified calcium silicate cements, focusing on issues related to their cytotoxicity and mineralization potential. An important question that remains unresolved in the dental literature is whether these materials are suitable for direct pulp capping. The aim of this review is to examine the available literature on the long-term clinical efficacy of resin-modified calcium silicate cements for direct pulp capping. A literature search was conducted using three electronic databases—PubMed, EBSCOhost, and Google Scholar—covering the period 2015–2026. Resin-modified calcium silicate cements represent the fourth generation of these materials, hardening through a combination of light polymerization and a hydration reaction. Issues related to their cytotoxicity, bioactivity, and clinical effectiveness were considered. The available literature mainly concerns TheraCal LC, with comparative data also available on the cytotoxicity of TheraCal PT relative to conventional calcium silicate cements. For most newer resin-modified calcium silicate cements, however, the main source of information remains the manufacturers, and further studies on their cytotoxicity and bioactivity are needed.

Keywords:
resin modified calcium silicate cement; direct pulp capping; cytotoxicity; bioactivity; fourth-generation biomaterial; hard-tissue dentine bridge

1. Introduction

Bioactive calcium silicate cements (CSCs) are widely used across various areas of endodontics, including regenerative endodontics [1].

The first such biomaterial, introduced into clinical practice by Torabinejad and White in 1993, was MTA (Original, Dentsply Tulsa Dental, Tulsa, OK, USA), representing the first generation of calcium silicate cements. Its chemical composition consists of a 4:1 ratio of Type I Portland cement to bismuth oxide, with the latter serving as a radiopaque agent [2].

A number of disadvantages associated with this first-generation calcium silicate cement—including a long setting time, handling difficulties, discoloration of hard dental tissues, low compressive strength, and high cost—led to the rapid development and introduction of new calcium silicate–based preparations into dental practice [3].

Numerous brands of these biomaterials, each with distinct physicochemical properties, are now available on the market.

1.1. Classification of Calcium Silicate Cements

The first-generation biomaterial is ProRoot (Dentsply Tulsa Dental, Tulsa, OK, USA), a hydraulic calcium silicate cement containing an inorganic bioactive compound, namely Type I ordinary Portland cement. This material is supplied as a powder–liquid combination that hardens through a hydration reaction [4].

The second generation comprises materials derived from modifications of first-generation MTA, including

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MTA Angelus and MTA Branco, among others. The third generation includes bioactive materials resulting from further modification of Portland cement, such as BioAggregate, Biodentine, Aureoseal, Ortho MTA, and MTA Plus. This generation also encompasses conventional calcium silicate cements supplied in powder–liquid form, which set through a hydration reaction that can occur under wet conditions [5].

Resin-modified calcium silicate cements belong to the fourth and most recent generation of these materials. These materials combine calcium silicates with a resin component and are indicated mainly for direct and indirect pulp capping [6]. Such procedures are conservative biological treatments aimed at preserving the vitality and function of the dental pulp (DP) through dentin bridge formation. The key difference between conventional and resin-modified calcium silicate cements is the presence of the resin component. The inclusion of monomers raises concerns about biocompatibility, given the possibility that residual unpolymerized monomers may come into contact with vital but inflamed dental pulp [7]. On the other hand, these monomers improve the physicochemical properties of the material, facilitate handling, and allow treatment to be completed in a single visit. The hydrophilic resin matrix also provides chemical adhesion to dentin, which is essential for achieving a hermetic seal at the pulp-exposure site [8].

Successful healing after direct pulp capping depends on several critical factors, including the type and stage of pulp inflammation (reversible), aseptic technique, hemorrhage control, and selection of an appropriate pulp-capping agent [9,10].

The choice of pulp-capping material is a critical determinant of clinical outcome. Clinicians expect bioactive materials with high clinical effectiveness and the capacity to form a high-quality dentin bridge, but there are still no definitive data on these materials regarding their long-term clinical effectiveness.

This review aims to provide a critical analysis and a comprehensive overview of the main issues associated with the clinical use and effectiveness of resin-modified calcium silicate cements.

2. Literature Search

A literature search was conducted across three electronic databases—PubMed, EBSCOhost, and Google Scholar—covering the period 2015–2026. The following keywords were used: resin-modified calcium silicate cements, clinical effectiveness, cytotoxicity, direct pulp capping, and residual monomers. Articles included and cited in the reference list were selected according to the inclusion and exclusion criteria described below.

2.1. Inclusion and Exclusion Criteria

Inclusion criteria: articles relevant to the chosen topic; language—fully accessible, open-access articles published in English; timeframe—2015–2026; publication type—peer-reviewed journal articles, patents, and books; treatment method—direct pulp capping; participant type—adults.

Exclusion criteria: articles not relevant to the chosen topic; articles published outside the specified timeframe; articles written in a language other than English; treatment method—vital extirpation; participant type—children.

3. Discussion

Resin-modified calcium silicate cements (RMCSC), also known as hybrid cements—their main representatives and chemical composition. These materials harden through a combination of light polymerization and a hydration reaction. The hydration reaction in this group of cements proceeds slowly, as it requires moisture supplied by the environment and depends on the rate of diffusion [11,12]. The first hybrid biomaterial was introduced into clinical practice in 2008 and consisted of a combination of 8% silica and 42.5% resin—comprising 20% Bis-GMA and 77.25% proprietary resin—together with 2.4% initiator and 5% barium sulfate [13].

The main representative of this generation is TheraCal LC (Bisco Inc., Schaumburg, IL, USA) [14], introduced into dental practice in 2011. According to the manufacturer, its chemical composition is presented in Table 1 [15–17]. The material is a one-component paste that hardens after 20 s of light polymerization per 1-mm increment, using a recommended curing-unit intensity of 1200 mW/cm^2 [14].

Bisco has since introduced a new dual-cure resin-modified calcium silicate cement, TheraCal PT, primarily indicated for pulpotomy in pediatric dentistry. It consists of synthetic Portland cement, a resin matrix of polyethylene glycol dimethacrylate (10–30%) and Bis-GMA (5–10%), barium zirconate (1–5%), and initiator (<1%) [8]. The material hardens after 10 s of light polymerization [14].

Another recent addition to the fourth generation is Bright MTA (Genoss, Suwon, Korea), the composition of which is presented in Table 1 [18,19].

BioCal Cap was introduced into clinical practice in 2019 (Figure 1). According to the manufacturer, this material combines 35–45 wt.% hydrophilic resin, Portland cement, and 7–12% barium sulfate, with a curing time of 40 s per increment under light polymerization [20]. For both of these newer materials, information in the litera-

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https://doi.org/10.69709/BIOMATC.2026.100602

ture regarding their properties remains limited. Their primary indications are direct and indirect pulp capping; however, resin-modified calcium silicate cements should also exhibit high mineralization potential and support the formation of a reparative dentin bridge [21]. A key requirement for any material intended for direct contact with the dental pulp during direct pulp capping is that it be non-cytotoxic and biocompatible [21].

Table 1: Composition of resin modified calcium silicate cements.

Resin Modified Calcium Silicate Cements	Chemical Composition
TheraCal lC	45% Type III Portland cement, 10% X-ray contrast agent—barium zirconate, and 45% resin represented by Bis-GMA, polyethylene glycol, and photoinitiator
TheraCal PT	Synthetic Portland cement, 1–5% barium zirconate, 10–30% polyethylene glycol dimethacrylate resin, and 5–10% Bis-GMA
Bright MTA	30–50% calcium silicates, 10–30% barium sulfate, resin—10–30% polyethylene glycol dimethacrylate, without containing Bis-GMA
BioCal Cap	Portland cement, 7–12% barium sulfate, 35–45 wt.% hydrophilic resin

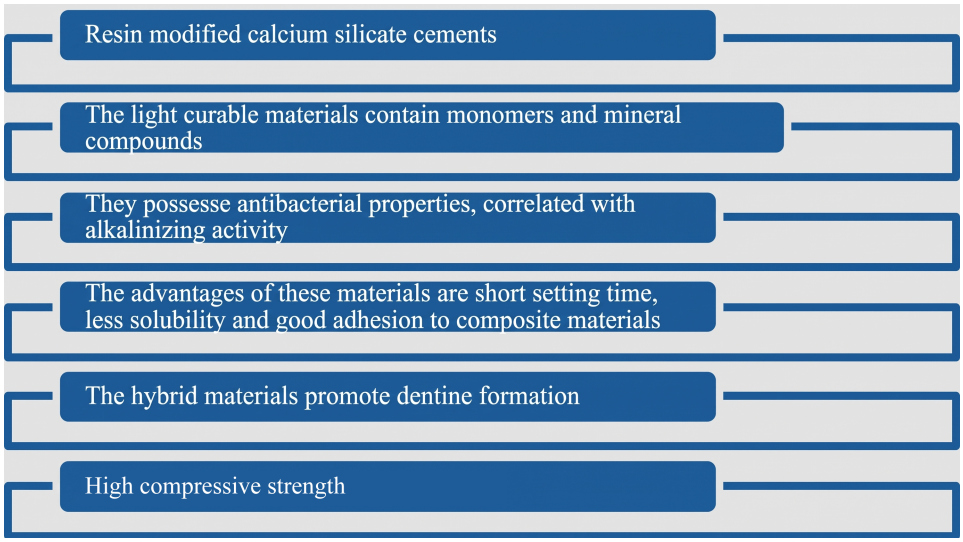


Figure 1: Basic properties of resin-modified calcium silicate cements.

According to Wataha [22] and Morsiya [23], a material is considered biocompatible when it elicits an appropriate biological response at the tissue level in a given application, without causing systemic or local toxicity, allergic reactions, mutagenic effects, or carcinogenic effects [24]. Biocompatibility testing involves a range of methods that vary depending on the site of application and duration of exposure [24,25]. Cytotoxicity refers to the capacity of a substance to induce cell damage or death, either directly or through the release of leachable components [26].

Cytotoxicity testing typically involves placing freshly prepared and/or hardened forms of the tested materials directly onto tissue cells, in order to evaluate whether the materials or their extracts promote cell death [27,28].

Available information in the literature regarding the cytotoxicity of these hybrid CSCs remains conflicting.

For example, Buonavoglia et al. [29] observed no cytotoxicity in osteoblast-like cells treated with TheraCal LC after 5 days, with the cells exhibiting normal organization.

In a comparative study of the cytotoxicity of different direct pulp-capping materials on pulp stem cells, Manaspon et al. found that both Dycal and TheraCal LC were cytotoxic to these cells [30]. Organic monomers released from hybrid materials were found to negatively affect the migration and proliferation of pulp stem cells [24].

Adığüzel et al. reported a significant reduction in the number of viable human pulp fibroblasts exposed to TheraCal LC [31]. Similar findings were reported by other au-

thors [32], who found that TheraCal LC significantly decreased viable human monocyte counts and induced significant DNA damage in the comet assay. Fathy et al. likewise reported a significant decrease in the number of viable mesenchymal stem cells after 24, 48, and 72 h of contact with TheraCal LC [33].

TheraCal LC has also been shown to exert damaging effects upon direct contact with human dental pulp stem cells [34,35]. According to Moradi et al. [36], TheraCal LC showed higher cytotoxicity toward human dental pulp cells than Calcimol LC and Dycal, but lower cytotoxicity than ACTIVA BioACTIVE and Fuji II LC.

In a study of the cytotoxicity of various pulp-capping agents using the mouse fibroblast BALB/3T3 cell line, cell viability with TheraCal LC at a 10% concentration was reported to be 68.18% [37]. TheraCal PT has also been found to release significantly lower amounts of bisphenol A-glycidyl methacrylate and polyethylene glycol dimethacrylate than TheraCal LC [38].

In a comparative study assessing the mineralization effect of MTA Angelus and the resin-modified cements TheraCal PT and TheraCal LC on human dental pulp stem cells (hDPSCs), TheraCal LC showed the lowest cell viability, whereas TheraCal PT demonstrated higher mineralization potential but reduced adhesion [39]. The authors attributed this to the higher hydrophilic resin content of TheraCal PT, which may improve interfacial interactions with the surrounding medium.

No cytotoxicity data are currently available for the other RMCSC formulations on the dental market, and the question of the cytotoxicity of resin-modified CSCs therefore remains open.

This may be attributed to the organic components present in hybrid CSCs, which can have a negative impact on clinical performance—possibly due to free unpolymerized monomers diffusing directly into the dental pulp [7,40]. These free unpolymerized monomers exert cytotoxic effects on pulp cells upon diffusion into pulp tissue [41,42]. Collado-González et al. found that although 30% of the total monomer content in RMCSC remains unpolymerized, most of it stays within the polymer matrix, with only around 9% diffusing into the dental pulp [43]. This is a complex process involving the degree of conversion after polymerization, the release of free monomers, and degradation of the resin matrix, all of which contribute to varying degrees of cytotoxicity [44].

Liu et al. found that hydrophobic monomers such as Bis-GMA and UDMA exert more cytotoxic effects than hydrophilic monomers such as HEMA and TEGDMA [45], a finding corroborated by other authors [24,45]. However, combinations of these monomers appear to produce a greater toxic effect than any single monomer alone, a finding also reported by Kraus et al. [46].

In our previous research, thermogravimetric analysis revealed that the new hybrid material BioCal Cap was more resistant than TheraCal LC, as no volatile compounds were detected. Subsequent gas chromatography–mass spectrometry (SIM mode) analysis showed that the TheraCal LC extract contained unreacted photoinitiators, whereas no unreacted HEMA monomers were detected in the BioCal Cap extract [47].

According to Nilsen et al. [48], hybrid TheraCal LC contains high levels of 2-(dimethylamino)ethyl methacrylate and camphorquinone, for which the manufacturer provides no adequate or relevant information.

3.1. Evaluating the bioactivity of RMCSC

Bioactivity is largely determined by the amount of calcium ions released, which stimulate dentinogenesis in dental pulp cells and promote the formation of an apatite layer within the biological environment. This bioactivity is attributed to the capacity of calcium silicate cements to release Ca ions, thereby initiating the differentiation and proliferation of odontoblast-like cells at the site of pulp exposure and promoting apatite crystal formation in a suitable environment [48–54].

The bioactivity of hybrid CSCs is commonly evaluated by measuring the amount of calcium ions released, since these ions play a key role in the differentiation of pulp cells into tissue-forming cells [55]. According to Elbanna et al. [56], calcium ion release from TheraCal LC decreased significantly over 14 days and declined sharply by 28 days, with values lower than those recorded for Biodentine over the same period.

In contrast, Al-Hyali et al. [57] found no statistically significant differences in calcium ion release between Biodentine and TheraCal LC over a 30-day comparison period. According to Camilleri et al. [58], calcium ion release from TheraCal LC is significantly low and ceases after the fourth day of application, which is attributable to the presence of the resin-modified matrix in the cured material. The amount of calcium ions released over 14 days by the newly introduced TheraCal PT was found to be significantly lower than that released by TheraCal LC.

In a comparative study, Gandolfi et al. [59] reported that TheraCal LC released significantly more calcium ions than either ProRoot MTA or Dycal over the same period. The same authors observed a decrease in hydroxyl ion release from TheraCal LC between days 7 and 14, which they suggested creates a favorable environment for the formation of new reparative dentin. Similar findings were reported by Kamal et al. [60], who concluded that

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https://doi.org/10.69709/BIOMATC.2026.100602

TheraCal LC has a low reparative capacity, producing a thin dentin bridge accompanied by inflammatory reactions in the dental pulp. Comparable findings regarding the lower mineralization-inducing potential of TheraCal compared to ProRoot were reported by Kang and Cherian et al. [61,62].

Although TheraCal LC contains resin ingredients, it appears to be a successful material for direct pulp capping provided it is properly cured.

The released calcium ions serve as bioactive signaling molecules for dentin bridge formation. Cannon et al. reported that a fully formed dentin bridge was achieved within 28 days of applying TheraCal LC as a direct pulp-capping agent [63]. Alkaline phosphatase is also an important enzyme influencing the healing process and creating conditions favorable for tissue calcification [64].

In a comparative study of TheraCal LC, RetroMTA, Biodentine, and ProRoot MTA in dog partial pulpotomy, a fully formed, high-quality dentin bridge was observed in only 33% of samples treated with TheraCal LC, while 75% of samples showed a low-quality dentin bridge [65]. Saber et al. [66] conducted a comparative study on the biological potential of Biodentine, NeoPutty, and TheraCal LC to induce proliferation and adhesion of human periodontal ligament stem cells, concluding that TheraCal LC lacks the potential to serve as an endodontic repair material. An in vivo study further established that TheraCal PT produced significantly greater hard-tissue formation than TheraCal LC when used as a direct pulp-capping agent [38].

In contrast, a similar comparative study conducted on mouse teeth found that a high-quality dentin bridge formed in all samples treated with TheraCal LC [67]. According to Singh et al., TheraCal LC histologically exhibits the characteristics of complete dentin bridge formation, with maximum dentin thickness [68].

Similar findings were reported by other authors [69], who found that all teeth treated with TheraCal LC by direct pulp capping formed a dentin bridge, which was complete and of good quality in 75% of cases.

In a comparative histological study of direct pulp capping on upper and lower premolars treated with TheraCal LC, a dentin bridge was found in all samples, with a thickness exceeding 0.25 mm in 60% of cases [67]. Similar findings were reported by Zeater et al. [70]. Further, mineralization capacity studies found that ProRoot MTA and TheraCal LC formed more calcium nodules than Biodentine [71,72].

Biomaterials used as pulp-capping agents should possess high mineralizing potential and the capacity to form a reparative tertiary hard-tissue barrier over the site of pulp exposure [73].

3.2. Evaluating and comparing the clinical effectiveness of RMCSC

RMCSCs are intended for use in direct and indirect pulp capping, with the goal of preserving the vitality, structural integrity, and functional integrity of the dental pulp. Materials used for this purpose must be bioactive, capable of stimulating dentinogenesis in the dental pulp, and possess a strong antibacterial effect [74].

A successful outcome of direct pulp capping depends critically on accurate assessment of the pulp inflammation status. Success rates for direct pulp capping in permanent teeth have been reported to range from 87.5% to 95.4% [75]. Data regarding the clinical effectiveness of RMCSC in direct pulp capping remain conflicting: while the reported curative effect of CSC in direct pulp capping ranges from 85% to 100% [76], the clinical effectiveness reported specifically for RMCSC ranges from 43% to 92%.

TheraCal LC used in direct pulp capping of permanent dentition has been reported to show a success rate of 93.3% over a 2-year period [77]. According to Wang et al., TheraCal LC is also a clinically effective pulp-capping agent in deciduous teeth [77].

TheraCal LC exhibited clinical and radiographic outcomes comparable to those of MTA in direct pulp capping of primary dentition at 12 months, with a success rate of 91.9% in the TheraCal group [78,79].

Meta-analyses comparing clinical and radiographic outcomes between resin-modified and conventional calcium silicate materials used as direct pulp-capping agents demonstrated that TheraCal LC achieved comparable short-term success to conventional materials [80].

Some authors, however, consider TheraCal LC unsuitable for direct pulp capping and recommend it only for indirect pulp capping [15,36,81,82].

Similar conclusions have been reached by other authors; based on histological findings, resin-based materials appear to be less suitable as pulp-capping agents than the conventional calcium silicate cement MTA [83].

A comparative clinical study with 6 months of follow-up found no statistically significant differences in dentin bridge quality among TheraCal LC, Biodentine, and ProRoot MTA; however, at 12 months, more complications—including severe inflammation and poorly formed dentin bridges—were reported [16].

Similarly good short-term clinical effectiveness of TheraCal LC at 6 months was reported by other authors [81]. The overall success rate of TheraCal LC as a direct pulp-capping agent was reported to be 96% at 1 month, 83% at 6 months, 73% at 1 year, and 72% at 3 years [50].

Comparable clinical success has been reported by other authors [73], who found favorable clinical and radiographic outcomes for both MTA and TheraCal LC over a 24-week follow-up period. Demarco et al. likewise reported good clinical results using TheraCal LC and iRoot BP Plus in direct pulp capping [75].

High long-term clinical effectiveness of TheraCal LC over 2- and 4-year periods was reported by Gary [15].

The clinical effectiveness of RMCSC is generally assessed using a combination of clinical indicators and radiographic data.

Clinical parameters used to assess effectiveness include spontaneous pain and objective examination findings such as sensitivity to percussion and palpation, mobility, swelling, and the presence of a fistula. Radiographic assessment criteria include continuity of the lamina dura, periapical lesion, furcation lesion, and pathological root resorption; the presence of one or more of these clinical or radiographic findings is considered treatment failure [84,85].

At the 12-month follow-up, these authors reported success rates of 63.2% for TheraCal PT compared with 96.0% for Biodentine [86]. In contrast, Jeanneau et al. [40] and Bakhtiar et al. [7] concluded that TheraCal LC is not a suitable agent for direct pulp capping, a conclusion also reached by Peskersoy et al. [50]. In a comparative clinical study of MTA Cerkamed (Poland), Biodentine, and TheraCal LC over a 36-month observation period, success rates of 84.75% and 79.4% were reported for MTA Cerkamed and Biodentine, respectively, versus 72.1% for the hybrid cement. A complete, well-formed dentin bridge was observed in 86.7% of cases in the MTA group, 85.7% in the Biodentine group, and 85.0% in the TheraCal LC group. The authors also reported a relationship between the size of the pulp exposure and clinical success: treatment success was 79.1% for exposures up to 0.5 mm and 63.5% for exposures between 0.6 and 1 mm. The quality of the hard-tissue bridge at the exposure site has been recognized as an important factor in the clinical success of direct pulp capping [86,87].

Overall, the literature reveals a lack of consensus regarding the long-term clinical efficacy of resin-modified CSCs in direct pulp capping.

The success of direct pulp capping depends on several critical factors, including the sealing properties of RMCSCs, adequate marginal adaptation, prevention of microleakage, and the formation of a hard-tissue bridge [88,89]. A meta-analysis by Silva et al. found that ProRoot MTA promoted better-organized, thicker hard-tissue bridges compared with RMCSC [88]. In a clinical histological examination, TheraCal LC showed higher rates of complete dentin bridge formation, with greater dentin thickness, compared with Biodentine [68].

A meta-analysis by Cabrera-Fernández et al. reported comparable short-term success between TheraCal LC and conventional CSC, underscoring the continuing lack of consensus on the long-term clinical efficacy of resin-modified CSCs in direct pulp capping [80].

4. Conclusions

This review of the literature clearly demonstrates the need for further research on resin-modified calcium silicate cements, particularly the newer materials now available on the dental market, for which the main source of information remains the manufacturers. Further studies on their cytotoxicity and mineralization potential are needed. An important conclusion emerging from this analysis is the need for definitive studies evaluating the long-term clinical effectiveness of these materials as direct pulp-capping agents. The question of their long-term clinical effectiveness and suitability for this purpose therefore remains open.

List of Abbreviations

Bis-GMA	Bisphenol A-glycidyl Methacrylate
CSC	Calcium Silicate Cement
DP	Dental Pulp
hDPSC	Human Dental Pulp Stem Cells
HEMA	2-hydroxyethyl Methacrylate
Hybrid CSCs	Hybrid Calcium Silicate Cements
MTA	Mineral Trioxide Aggregate
RMCSC	Resin Modified Calcium Silicate Cements
TEGDMA	Triethylene Glycol Dimethacrylate
UDMA	Urethane-dimethacrylate

Author Contributions

The author confirms that she was solely responsible for the conceptualization, methodology, formal analysis, investigation, resources, data curation, writing—original draft preparation, writing—review and editing, and visualization of the article. The author has read and agreed to the published version of the manuscript.

Conflicts of Interest

The author declares no conflicts of interest.

Funding

The study did not receive any external funding and was conducted using only institutional resources.

Acknowledgments

I sincerely thank the Editorial Board Members and reviewers for their valuable time, expert assessment, and contributions throughout manuscript processing.

AI Declaration

The author confirms that no AI tools were used to generate any content of this manuscript. The author takes full responsibility for the accuracy, originality, integrity, and scientific content of the manuscript.

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