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Radiographic and Clinical Union Rates After Injectable Osteogenic Substitute in Comminuted Condylar Fractures

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ABSTRACT

Background: Comminuted mandibular condylar fractures present cancellous, often hypovascular bone stock that limits the mechanical purchase of conventional miniplate and screw fixation, yet radiographic and clinical union has rarely been reported as a discrete, scored outcome in the condylar fracture literature relative to occlusal and functional endpoints. Objective: This narrative review synthesizes the published evidence relevant to injectable osteogenic substitutes-calcium phosphate and calcium sulfate cements, hydroxyapatite cement, and bioactive glass-as adjuncts to fixation in comminuted condylar fractures, with a specific focus on radiographic and clinical union rates. Methods: Literature relevant to condylar fracture imaging and union assessment, injectable osteogenic substitute materials science, union and healing outcomes in analogous comminuted fracture augmentation, and malunion/nonunion risk in mandibular fracture fixation was identified and narratively synthesized across five thematic domains. Findings: No dedicated condylar fracture trials of injectable osteogenic substitutes were identified. Indirect evidence is nonetheless coherent: calcium phosphate cement augmentation reduced fixation failure and supported essentially complete radiographic consolidation in comminuted tibial plateau and proximal humeral fractures analogous to the condylar head, bioactive glass achieved union rates statistically comparable to autologous bone graft (77% versus 78% complete fusion) even in infected, biologically compromised nonunion, and hydroxyapatite cement carries a quantified safety profile across nearly 2000 craniofacial reconstruction cases. Malunion and nonunion analyses of mandibular fractures identify comminution, posterior fracture location, and treatment delay as the principal risk factors for failed union, and open reduction consistently outperforms closed treatment on these endpoints. Conclusions: Injectable osteogenic substitutes have a coherent materials rationale and a supportive analogous-fracture evidence base for improving union in comminuted condylar fractures, but this application remains biologically plausible rather than clinically proven. Prospective studies applying structured, quantitative radiographic union metrics to condylar fractures treated with and without substitute augmentation are needed before routine adoption can be recommended.

Keywords: *injectable bone substitute; mandibular condylar fracture; radiographic union; calcium phosphate cement; bioactive glass osteoconduction*

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Introduction

Union—the restoration of mechanical and biological continuity across a fracture line—is the outcome that ultimately determines whether any fixation strategy for the mandibular condyle has succeeded, yet it has historically been reported inconsistently, or not at all, in the condylar fracture literature relative to occlusion, mouth opening, and pain. Most comparative series of open versus closed treatment of condylar fractures report functional surrogates such as maximum interincisal opening, lateral excursion, and occlusal disturbance rather than a structured radiographic union score [1,2,3,4], leaving a persistent gap in the evidence base regarding how quickly, how completely, and by what imaging criteria bony continuity is actually re-established across comminuted, cancellous, and frequently avascular condylar fragments. This gap matters clinically because the condylar head and neck are small, densely trabecular structures with a tenuous intracapsular blood supply, and comminution—by fragmenting the cortical shell that would otherwise provide mechanical scaffolding for callus formation—removes much of the structural substrate on which spontaneous union depends [5].

Injectable osteogenic substitutes, principally calcium phosphate and calcium sulfate cements and bioactive glass formulations, have been proposed as adjuncts capable of filling these comminution-related voids, buttressing miniplate and lag-screw fixation in cancellous bone, and providing an osteoconductive scaffold that may accelerate radiographic consolidation relative to fixation alone [6,7]. Their union-relevant rationale differs somewhat from that of graft materials used purely to restore volume: in load-bearing metaphyseal and articular fractures elsewhere in the skeleton, injectable cements have been shown not only to fill voids but to measurably reduce mechanical failure of the adjacent fixation construct, a mechanism directly transferable to comminuted condylar neck and subcondylar fractures where screw purchase in fragmented cancellous bone is often marginal [8,9]. Whether this translates into faster or more complete radiographic and clinical union specifically in the mandibular condyle, however, has not been established by dedicated condylar trials, and the present narrative review is organized around closing that specific gap in the synthesis.

This review addresses five interlocking questions. First, how is union in the condyle actually assessed radiographically and clinically, and what imaging tools and scoring frameworks are available or transferable from long-bone practice? Second, what are the material mechanisms by which injectable osteogenic substitutes are hypothesized to influence union kinetics? Third, what union and healing rates have actually been reported when these materials are used to augment fixation in analogous comminuted, cancellous-bone-deficient fractures in orthopedics and general craniomaxillofacial surgery? Fourth, what do existing condylar fracture series reveal about malunion, nonunion, and the complications that compete with or confound union assessment? And fifth, what would a union-focused evidence base for injectable substitutes in condylar fracture surgery need to look like going forward? Synthesizing across these questions, we argue that while direct condylar union data for injectable osteogenic substitutes remain essentially absent, the indirect evidence from analogous fracture augmentation and from the condylar fracture complication literature is coherent enough to justify prospective, union-endpoint-driven clinical evaluation.

Assessing Radiographic and Clinical Union in Mandibular Condylar Fractures

Union assessment in the condyle is complicated by the region's anatomy: overlapping cortical and dental structures obscure plain radiographs and panoramic views, and even multidetector computed tomography, while highly sensitive for acute fracture detection, has not been paired with a validated, condyle-specific scoring instrument analogous to those used in long-bone trauma. Naeem and colleagues' review of imaging in traumatic mandibular fractures confirmed that CT is the modality of choice for acute condylar injury, citing sensitivity approaching 100% with multiplanar and three-dimensional reconstruction, while panoramic radiography, though useful for the mandibular body and angle, poorly delineates condylar displacement and comminution [10]. This diagnostic strength at the acute stage does not automatically extend to longitudinal healing assessment, and the condylar fracture literature has generally lacked a structured, reproducible radiographic union scale of the kind developed for the long bones.

The most influential such instrument outside the craniomaxillofacial skeleton is the Radiographic Union Score for Tibial fractures (RUST), developed by Whelan and colleagues by scoring cortical bridging and callus formation across four cortices on orthogonal radiographs, which demonstrated substantially improved interobserver and intraobserver reliability compared with earlier ad hoc healing assessments and has since been adapted and validated across multiple long-bone and pediatric fracture contexts [11]. No directly analogous, validated scoring system for condylar union has been reported, and the condylar fracture literature has instead relied on qualitative radiographic descriptors—cortical continuity, resorption at the fracture margin, and remodeling of ramus height—embedded within broader postoperative follow-up protocols. Gabryelczak and Kozakiewicz's quantitative computed-tomographic study of bone status at the osteosynthesis plate after healing in condylar process fractures represents one of the more granular recent attempts to characterize this: measuring peri-screw bone resorption directly rather than relying on a categorical union/non-union judgment, they found mean bone loss around screw heads of 0.4 ± 0.7 mm (maximum 0.6 ± 0.9 mm), with resorption significantly greater when plates were positioned within 14 mm of the lateral condylar pole ($p < 0.001$) and significantly reduced when nine or more screws were used ($p < 0.05$), while emphasizing that this resorption did not compromise clinical union or ramus height in most cases [12]. This kind of quantitative, CT-based metric—rather than a binary union call—is precisely the outcome architecture into which injectable substitute augmentation would need to be evaluated, since a material intended to buttress fixation and reduce peri-screw bone loss should, in principle, be assessable using the same resorption and cortical-bridging metrics this study established for unaugmented plates.

Injectable Osteogenic Substitutes: Composition and Union-Relevant Mechanisms

The materials proposed for condylar fracture augmentation fall into three broad families, each with a distinct chemistry that bears directly on how, and how quickly, they might influence union. Calcium phosphate cements set through a dissolution–precipitation reaction into a nanocrystalline apatite or brushite matrix that approaches the compressive strength of cancellous bone once cured, and were characterized in Larsson and Bauer's foundational review as combining injectability with sufficient early mechanical support to buttress an adjacent fixation construct while osteoconductive remodeling proceeds over subsequent months [6]. Because these cements are largely resorbed and replaced by host bone rather than remaining as a permanent implant, their union-relevant behavior is time-dependent: early mechanical support gives way to progressive osteoconductive substitution, a two-phase profile that Larsson and Hannink's survey of commercial injectable bone-graft substitute products extended to calcium sulfate and composite formulations, noting that resorption kinetics differ substantially across products and are a primary determinant of how quickly a given material's contribution to construct stability is replaced by native bone [7].

Calcium sulfate–based materials, the second family, resorb considerably faster than calcium phosphate cements—often within weeks—which limits their independent mechanical contribution to fixation but may reduce the risk of a persistent radiolucent or radiopaque residuum that could confound later radiographic union assessment, an important practical consideration for any material intended for use in the condyle where postoperative imaging is relied upon to judge healing. Hydroxyapatite cement, introduced by Friedman and Costantino

for craniofacial contour and skeletal defect repair, sets in situ into a mineral composition closely resembling bone and has accumulated a substantial safety record in cranial and mid-facial reconstruction, though it is understood to remodel more slowly and less completely than calcium phosphate or calcium sulfate cements, behaving in some series more as a long-term space-filler than as a fully resorbable osteoconductive scaffold [13].

Principal injectable osteogenic substitute material classes and their union-relevant setting mechanism, resorption behavior, and reported clinical role.

Material class	Setting/union mechanism	Resorption behavior	Key reference
Injectable calcium phosphate cement	Dissolution-precipitation into nanocrystalline apatite/brushite; buttresses fixation while remodeling proceeds	Gradual resorption over months, substituted by host bone	Larsson & Bauer 2002; Egol et al. 2012; Peng et al. 2024
Calcium sulfate cement/composites	Rapid dissolution, early void filling	Fast resorption (weeks), limited persistent mechanical contribution	Larsson & Hannink 2011
Hydroxyapatite cement	In situ moldable apatite cement, minimal remodeling	Slow, often incomplete resorption; long-term space filler	Friedman & Costantino 1997; Elemosho et al. 2024
Bioactive glass	Surface ion exchange, hydroxycarbonate apatite layer formation (osteostimulative)	Progressive resorption with new bone ingrowth	Profeta & Huppa 2016; Steinhausen et al. 2021; Saghiri et al. 2025; Naaz 2026
Doped/composite calcium phosphate for jaw regeneration	Ceramic setting with bioactive dopants tuned to local union timeline	Investigational, resorption rate under active development	Mostafavi Moghaddam et al. 2025

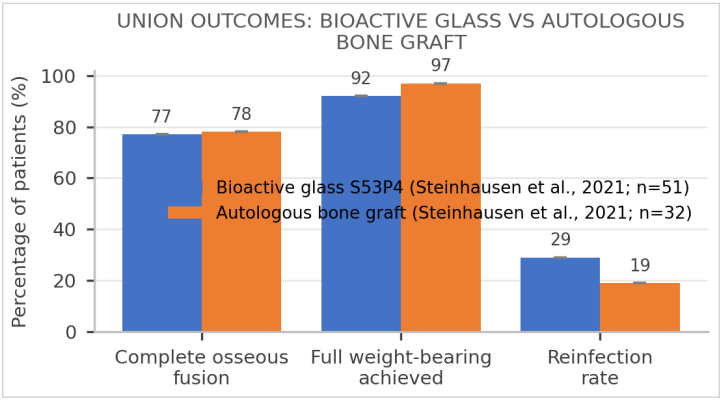
Bioactive glass, the third family, differs mechanistically from both cement classes: rather than setting through a purely chemical reaction, it undergoes surface ion exchange on contact with physiological fluid, forming a hydroxycarbonate apatite layer that actively supports osteoblast attachment and mineralization, a genuinely osteostimulative rather than purely osteoconductive mechanism. Profeta and Huppa's review catalogued this behavior across alveolar, sinus, and periodontal maxillofacial applications [14], and Naaz's more recent survey of NovaBone-type bioactive glass formulations detailed comparable mechanisms and handling characteristics specifically for oral bone regeneration [15]. Mostafavi Moghaddam and colleagues' bench-to-bedside review of calcium phosphate materials for maxillomandibular regeneration emphasized that ongoing formulation work—doping, composite reinforcement, and resorption-rate tuning—is aimed precisely at matching a material's degradation profile to the union timeline of the bone it is meant to support, underscoring that the choice among these material families for condylar augmentation is not merely one of availability but of matching resorption kinetics to the biological union timeline of a small, cancellous, and often hypovascular fracture fragment [16].

Union and Healing Outcomes in Analogous Fracture Augmentation

Representative studies reporting quantitative union, healing, or malunion/nonunion outcomes relevant to injectable osteogenic substitute use in comminuted condylar fracture fixation.

Study	Fracture/defect type	Intervention	Union-related finding
Iundusi et al. 2015	Depressed tibial plateau fracture (n=24)	Injectable CaP/CaSO4 cement (CERAMENT)	Complete radiographic remodeling by mean 5 months; residual depression 1.18 mm; excellent/good outcome in 100%
Egol et al. 2012	Proximal humeral fracture, locked plating	Calcium phosphate cement void augmentation	Significantly reduced secondary screw penetration versus plating alone
Peng et al. 2024	Elderly proximal humeral fracture (n=20)	Locking plate + calcium phosphate cement	No fixation failure, cut-through, or nonunion at 3-6 months
Steinhausen et al. 2021	Chronic osteomyelitis / infected nonunion (n=83)	Bioactive glass S53P4 (n=51) vs autograft (n=32)	Complete osseous fusion 77% (BAG) vs 78% (autograft)
Gabryelczak & Kozakiewicz 2026	Mandibular condylar process fracture, ORIF	Conventional plate/screw fixation (no substitute)	Peri-screw bone resorption 0.4+/-0.7 mm; greater near lateral pole ($p<0.001$), reduced with >=9 screws ($p<0.05$)

Bone union/fusion and functional outcomes with bioactive glass S53P4 versus autologous bone graft in 83 patients treated for chronic osteomyelitis and infected non-unions, the largest directly comparative union-rate dataset available for an injectable osteogenic substitute in a biologically compromised, bone-deficient healing environment analogous to comminuted condylar fracture bone stock (Steinhausen et al., 2021).



Because dedicated condylar trials of injectable osteogenic substitutes do not exist, the most informative union data come from anatomically and biomechanically analogous fractures elsewhere in the skeleton and from bioactive glass applications in infected or defect-associated bone elsewhere in the craniomaxillofacial and orthopedic literature. In the orthopedic literature, Iundusi and colleagues followed 24 patients with depressed tibial plateau fractures augmented with injectable calcium phosphate/sulfate cement (CERAMENT) for a mean of 44

months, reporting complete radiographic resorption and remodeling of the cement by a mean of 5 months, residual joint depression averaging only 1.18 mm, and functional results rated excellent or good in 100% of patients, with no cement-attributable complications—an outcome profile suggesting that, in a comminuted, cancellous-bone-deficient articular fracture pattern closely analogous to the condylar head, injectable cement augmentation is compatible with rapid and essentially complete radiographic consolidation [17]. Egol and colleagues demonstrated a complementary mechanical benefit in proximal humeral fractures, showing that intraoperative calcium phosphate cement augmentation of the fracture void during locked plating significantly reduced secondary screw penetration into the joint compared with plating alone, directly supporting the buttressing mechanism most relevant to comminuted condylar neck fixation [8]. More recently, Peng and colleagues' single-center series of 20 elderly patients treated with locking-plate fixation augmented with calcium phosphate bone cement for proximal humeral fractures reported no fixation failure, screw cut-through, loss of fixation, or nonunion at three- and six-month follow-up, with mean pain scores falling from 1.66 to 0.42 over that interval—again consistent with augmentation supporting, rather than impeding, union in comminuted metaphyseal bone [9].

Bioactive glass has generated the most directly quantified union comparisons, largely from its use in infected nonunion and osteomyelitis defects, a clinical scenario that shares with comminuted condylar fractures both bone-stock deficiency and impaired local biology. Steinhausen and colleagues' single-center comparative study of 83 patients with chronic osteomyelitis or infected nonunions treated with either bioactive glass S53P4 (n = 51) or autologous bone graft (n = 32) found complete osseous fusion in 77% of the bioactive glass group versus 78% of the autograft group, with full weight-bearing achieved in 92% versus 97% respectively, leading the authors to conclude that bioactive glass was neither superior nor inferior to autograft with respect to union and functional outcome [18]. This near-equivalence in a biologically compromised healing environment is an encouraging, if indirect, signal for condylar application, since it suggests that a material free of donor-site morbidity can support union rates comparable to the historical gold standard even where local bone biology is impaired. In the maxillofacial skeleton specifically, Saghiri and colleagues' systematic review and meta-analysis found comparable or favorable radiographic bone fill and complication profiles for bioactive glass against traditional autogenous and allogeneic grafts across pooled clinical series [19], while hydroxyapatite cement's largest available outcome synthesis—Elemosho and colleagues' pooled analysis of 1,983 patients across 35 craniofacial reconstruction studies—reported infection or explantation rates ranging from 1.5% (retrosigmoid cranioplasty) to 7.5% (large defect cranioplasty), figures that, while not condylar-specific, establish a reassuring safety envelope for hydroxyapatite cement placement within the facial skeleton more broadly [20].

Malunion, Nonunion, and Complication Risk in Condylar Fracture Fixation

Any assessment of where injectable osteogenic substitutes might improve condylar union outcomes must be grounded in what is already known about malunion and nonunion rates after conventional condylar fixation, since these rates define both the baseline against which an adjunctive material would need to demonstrate benefit and the fracture subgroups—comminuted, bone-deficient, delayed-presentation—in which such benefit is most plausible. Tadepalli and colleagues' scoping review of risk factors and interventional predictors for postoperative malunion and nonunion in adult mandibular fractures found that closed reduction with maxillomandibular fixation carried a substantially higher malunion rate than open reduction and internal fixation (13.3% versus 0%, $p < 0.05$), and that among comminuted fractures specifically, closed treatment carried a 6.7% nonunion rate compared with 0% for ORIF ($p < 0.03$); the review further identified surgical approach (transbuccal versus intraoral ORIF, 1.1% versus 11.1% nonunion, $p = 0.005$), treatment delay beyond seven days (12.5% versus 2.4% malunion for earlier surgery, $p = 0.043$), posterior fracture location, advancing age, and active smoking as independent risk factors for impaired union [21]. These findings reinforce that comminution, delay, and posterior (condylar/subcondylar) location are precisely the conditions under which union is least assured by fixation hardware alone—the same conditions in which injectable substitute augmentation has the clearest theoretical rationale.

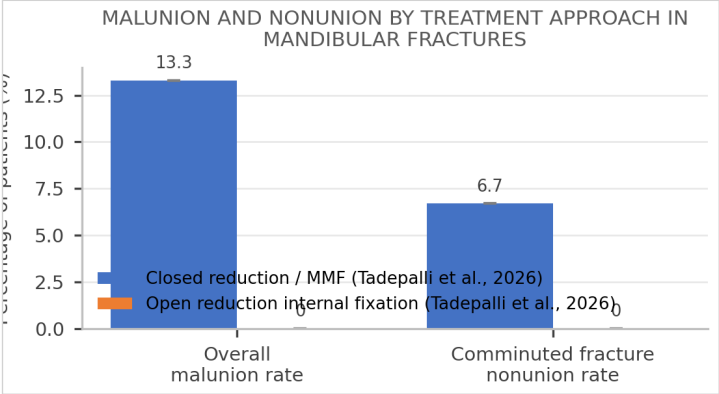
Boffano and colleagues' review of surgical treatment options for condylar head fractures specifically identified insufficient bone stock and fragment comminution as recurring technical obstacles limiting the applicability of conventional miniplate and screw fixation, occasionally necessitating alloplastic replacement when the fragment cannot be reconstructed [5], while broader comparative and meta-analytic literature on open versus closed condylar treatment—though centered on occlusal and functional endpoints rather than union per se—has consistently found that ORIF reduces malocclusion and improves several functional parameters relative to closed treatment, at the cost of increased infection and facial nerve injury risk [2,4]. The 2021 Cochrane update on interventions for condylar fractures cautioned that the underlying trial evidence remains limited in quantity and quality, a caveat that applies with even greater force to the union-specific literature, since union has rarely been reported as a discrete, scored endpoint in these trials at all [3]. Complication data from ORIF series further contextualize the risk of any additional intraoperative step: Agier and colleagues' series of 329 patients found facial nerve dysfunction in 50.45% postoperatively, but with complete restoration of function in 98.16% of affected patients by final follow-up and permanent injury in only 1.82%, indicating that the operative morbidity attending open exposure adequate for hardware placement—and, by extension, for any injectable substitute delivery—is common but overwhelmingly reversible [22].

Toward Evidence-Based Integration of Injectable Substitutes into Condylar Fracture Union Protocols

Synthesizing the union-focused evidence assembled above yields a coherent but still indirect case for injectable osteogenic substitute use in comminuted condylar fracture fixation. On the mechanistic and materials side, calcium phosphate and calcium sulfate cements and bioactive glass formulations have well-characterized, union-relevant resorption and osteoconductive or osteostimulative behavior [6,7,13,14,15,16]. On the analogous-fracture outcome side, calcium phosphate cement augmentation has been shown to reduce fixation failure and support rapid, essentially complete radiographic consolidation in comminuted metaphyseal and articular fractures closely resembling the condylar head and neck in bone quality and comminution pattern [17,8,9], while bioactive glass has achieved union rates statistically indistinguishable from autologous bone graft even in biologically compromised, infected nonunion

settings [18,19], and hydroxyapatite cement has an established, quantified safety profile across thousands of craniofacial reconstruction cases [20]. On the condylar-specific side, the fracture patterns in which conventional fixation most often fails to achieve prompt union—comminuted, posteriorly located, delayed-presentation fractures—have been explicitly identified by dedicated malunion/nonunion analyses [21,5], giving a target population for future augmentation trials.

Malunion and nonunion rates after closed reduction versus open reduction and internal fixation (ORIF) of mandibular fractures, overall and restricted to comminuted fractures, from a scoping review of risk factors and interventional predictors for postoperative union failure (Tadepalli et al., 2026), defining the comminuted, fixation-limited subgroup in which injectable osteogenic substitute augmentation has the clearest theoretical role.



What remains absent is the connective tissue between these two evidence bases: a prospective or comparative series that applies a structured, quantitative union metric—whether an adaptation of RUST-style cortical bridging scoring [11] or a CT-based peri-hardware resorption metric of the kind developed by Gabryelczak and Kozakiewicz [12]—to condylar fractures treated with and without injectable substitute augmentation, tracking time-to-union, final union rate, and their correlation with functional and occlusal recovery already established as clinically meaningful in this fracture type [2,4]. Such a study would need to standardize imaging timing (given that CT best characterizes the acute injury but has not been systematically applied at fixed postoperative intervals for condylar healing surveillance [10]), pre-specify a comminution grading system to enable stratified analysis of the subgroup most likely to benefit, and report union alongside—not instead of—the infection and facial nerve morbidity that any additional intraoperative step must be shown not to meaningfully worsen [22,3]. Until such union-endpoint-driven data accumulate, the rational deployment of injectable osteogenic substitutes in condylar fracture surgery should remain restricted to comminuted or bone-deficient fractures selected on a case-by-case basis, with explicit acknowledgment that the supporting evidence, while mechanistically and analogically strong, has not yet been generated in the condyle itself.

Conclusion

Radiographic and clinical union has been an underreported outcome in the mandibular condylar fracture literature, which has instead concentrated on occlusal and functional endpoints in the long-running open-versus-closed treatment debate [2,3,4]. Injectable osteogenic substitutes—calcium phosphate and calcium sulfate cements, hydroxyapatite cement, and bioactive glass—carry a coherent, union-relevant mechanistic rationale and a supportive body of analogous evidence from comminuted metaphyseal and articular fracture augmentation and from infected nonunion management, where union rates with these materials have approached or matched those of autograft and conventional fixation [17,8,9,18,20]. Malunion and nonunion analyses in mandibular fracture care consistently identify comminution, posterior location, and treatment delay as the principal risk factors for failed union [21,5]—precisely the clinical scenario in which injectable substitute augmentation has the strongest theoretical justification. Realizing this potential will require condylar fracture studies that adopt a structured, quantitative radiographic union metric [11,12] and report time-to-union and final union rate as primary endpoints alongside the functional, occlusal, and complication outcomes already tracked in this field [22,10], transforming a biologically plausible extrapolation into a directly tested clinical practice.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Lombardi M conceived the review, conducted the literature search, and drafted the manuscript. Parn M contributed radiological context on union assessment and critically revised the manuscript for important intellectual content. Stanciu F contributed additional orthopedic biomaterials framing and approved the final version for submission.

Ethics Statement

Not applicable. This is a narrative review of previously published literature and did not involve new experimental data, human participants, or animal subjects.

Data Availability

No new data were generated or analyzed for this review. All sources synthesized are cited in the reference list and are available through their original publishers.

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