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Osteobiology and Arthrodesis in Spinal Surgery: A Systematic Review for the Neurosurgeon

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Abstract

Spinal arthrodesis is a common surgical procedure for treating degenerative, traumatic, and deformative pathologies, with osteobiology playing a fundamental role in spinal fusion. Although autografts are the gold standard due to their osteogenic capacity, they are associated with significant morbidity. This has led to the development of alternative biomaterials, such as allografts, demineralized bone matrices (DBM), and bone morphogenetic proteins (BMP). This systematic review aimed to analyze the effectiveness and safety of osteobiological materials used in spinal arthrodesis, focusing on their properties and the influence of internal fixation on fusion rates. A literature search was conducted in scientific databases following the PRISMA methodology, selecting studies that evaluated fusion rates, complications, and osteointegration in spinal surgery. Results showed that BMP-2 achieved fusion rates of 92%, while autografts reached 100% but with higher morbidity. The combination of internal fixation with bone grafts improved biomechanical stability and reduced bone resorption. Additionally, the use of teriparatide and zoledronic acid optimized bone consolidation in osteoporotic patients. These findings suggest that graft selection should be individualized, considering patient-specific factors and optimizing internal fixation to enhance clinical outcomes in spinal arthrodesis.

Keywords

Arthrodesis, Osteobiology, Bone Grafts, Spinal Fusion, Osteoinduction

1. Introduction

Spinal surgery has significantly advanced in recent decades due to a deeper understanding of osteobiology and the development of biomaterials designed for arthrodesis. Spinal fusion is widely used to manage various degenerative, traumatic, and deformative spinal conditions, aiming to promote bone union through biological grafts and synthetic substitutes.

In this context, osteogenesis, osteoconduction, and osteoinduction are essential for graft integration and the success of arthrodesis. **Osteogenesis** refers to generating new bone tissue from osteoprogenitor cells in the graft. **Osteoconduction** is the process where a three-dimensional matrix serves as a scaffold for the growth and proliferation of bone cells from the host bone. **Osteoinduction** involves stimulating mesenchymal cells to differentiate into osteoblasts, promoting bone formation in areas where it would not normally occur [1].

Although these concepts have been extensively studied and applied in orthopedics, their understanding and application in neurosurgery present unique challenges. The proximity of critical neurological structures in spinal surgeries increases the risk of complications, such as spinal cord and nerve root injuries, which may result in significant neurological deficits. Additionally, complex pathologies, such as intradural tumors and scoliotic deformities, necessitate meticulous surgical planning and careful selection of osteobiological materials to minimize risks and optimize outcomes.

Despite multiple options, iliac crest autografts remain the gold standard due to their superior osteogenic properties. However, the limitations associated with their harvesting, such as donor site morbidity, have driven the search for alternatives with comparable biological properties and a lower risk of complications. For instance, studies have demonstrated that demineralized bone matrices (DBM) combined with bone marrow aspirate can provide fusion rates similar to autografts, allowing for a reduced quantity of autograft while still achieving successful arthrodesis [2].

This systematic review analyzes current evidence on the use of osteobiological materials in spinal arthrodesis and their applicability in neurosurgical practice. It explores the biomechanical and biological characteristics of various graft types, including autografts, allografts, demineralized bone matrices, bone morphogenetic proteins, and ceramic devices, along with their impact on fusion rates and clinical outcomes. The role of internal fixation and recipient site optimization will also be discussed as critical factors in enhancing osteointegration. By providing an updated, evidence-based analysis, this study aims to guide neurosurgeons in selecting optimal strategies for spinal arthrodesis, ultimately contributing to improved surgical outcomes and enhanced patient quality of life.

2. Objectives

2.1. General Objective

To analyze the available scientific evidence on the use of osteobiological materials

in spinal arthrodesis, emphasizing their applicability in neurosurgical practice to optimize clinical outcomes and reduce complications associated with spinal fusion.

2.2. Specific Objectives

1) To describe the main types of bone grafts and biomaterials used in spinal arthrodesis, including their osteogenic, osteoinductive, and osteoconductive properties.

2) To evaluate the effectiveness and safety of different osteobiological materials in spinal fusion, considering success rates, complications, and factors influencing osteointegration.

3) To determine the impact of internal fixation and recipient site preparation on the effectiveness of arthrodesis, establishing evidence-based recommendations for neurosurgical practice.

3. Methodology

3.1. Study Design

This study is a systematic review of scientific literature, following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology; see Figure 1.

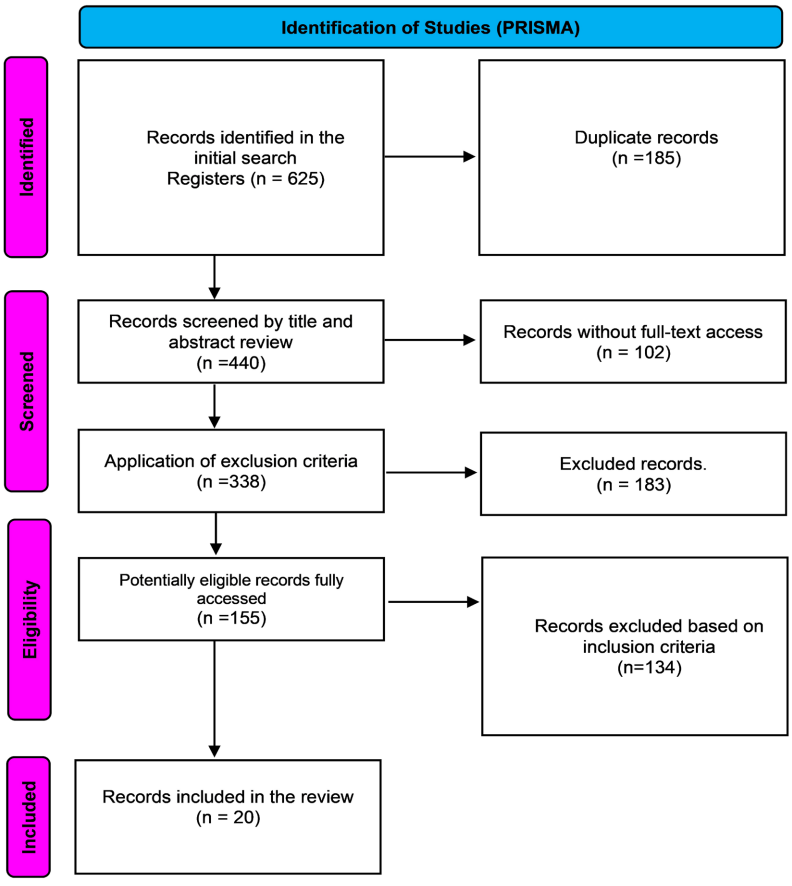

Figure 1. PRISMA model.

The literature search will be conducted in recognized scientific databases, including PubMed, Scopus, Web of Science, Embase, and the Cochrane Library. Search terms will combine keywords and Boolean operators, such as "spinal fusion," "bone grafts," "osteobiologics," "neurosurgery," "bone substitutes," "arthrodesis," and "osteoconductive materials," among others. Filters will include studies published within the last 10 years in English and Spanish.

3.2. Inclusion Criteria

- Original studies and systematic reviews on the use of osteobiological materials in spinal arthrodesis.
- Clinical trials, observational studies, and meta-analyses published in indexed journals.
- Studies reporting fusion rates, complications, and clinical efficacy of bone grafts and biomaterial substitutes.
- Research conducted on human subjects in the context of neurosurgery or spinal surgery.

3.3. Exclusion Criteria

- Studies conducted on animal models or in vitro without direct clinical application.
- Case reports or case series with fewer than 10 patients.
- Publications without full-text access or those not meeting the minimum methodological standards for a systematic review.

3.4. Study Selection and Evaluation

The selection process for articles will be conducted in three phases, following the PRISMA flowchart:

1) Removal of duplicates after searching multiple databases.

2) Screening of titles and abstracts to exclude studies that do not meet the inclusion criteria.

3) Full-text evaluation of selected articles, applying methodological quality assessment tools such as the Newcastle-Ottawa Scale for observational studies and the Cochrane Risk of Bias Tool for clinical trials.

3.5. Data Synthesis and Analysis

The extracted data will include information on study design, type of graft or osteobiological material used, fusion rates, reported complications, and clinical outcomes. The findings will be presented in comparative tables, and if homogeneous quantitative data are obtained, the feasibility of conducting a meta-analysis will be explored.

4. Results

Based on the study selection process, the following results table was created (see Table 1):

Table 1. Systematic review.

Author	Sample	Methodology	Results
Álvarez-Galovich *et al.*, 2023	Patients undergoing spinal surgery with ERAS protocols	A literature review and analysis of Enhanced Recovery After Surgery (ERAS) strategies in spinal surgery patients.	Evaluated the use of teriparatide, showing a 30% higher fusion rate compared to bisphosphonates, with improved bone consolidation. No specific complications were detailed.
Boden & Schimandle, 1995	Biomechanical study on animal and human models	Experimental study using animal models and biomechanical analysis in humans to assess osteogenesis in spinal arthrodesis.	Compared the use of DBM Grafton with iliac crest bone graft (ICBG). Fusion rates were 86% with DBM and 92% with autograft at 2 years. No significant complications related to the osteobiological material were reported.
Burkus *et al.*, 2009	Patients with lumbar fusion using BMP-2 (6-year follow-up)	A clinical trial with a 6-year follow-up of patients undergoing lumbar arthrodesis with BMP-2 compared radiological and clinical outcomes.	Results showed that BMP-2 significantly increased spinal fusion rates and reduced the need for revision surgery compared to autografts.
Chen *et al.*, 2012	Osteoporotic patients undergoing lumbar fusion	A comparative clinical trial evaluated the efficacy of zoledronic acid in the fusion rates of osteoporotic patients undergoing lumbar fusion.	The study examined the effect of zoledronic acid and found a 20% increase in graft density and a reduction in the incidence of pseudoarthrosis. No significant complications were reported.
Debono *et al.*, 2021	Review of perioperative strategies in lumbar fusion	A systematic literature review and expert consensus on perioperative strategies to improve lumbar fusion outcomes.	Evidence-based recommendations were established to enhance perioperative management in spinal surgery, optimizing postoperative recovery.
Díaz-Romero Paz & Reimunde, 2018	Osteoporotic patients undergoing spinal surgery	Retrospective analysis of osteoporotic patients undergoing spinal surgery, evaluating different medical strategies to enhance bone fusion.	Analyzed procedures using pedicle screws showed a success rate above 90% and greater biomechanical stability. Screw loosening or implant migration was reported in 5% to 10% of cases.
Dimar *et al.*, 2006	Patients undergoing lumbar arthrodesis using BMP-2	Prospective clinical trial comparing the use of BMP-2 versus autograft in patients undergoing lumbar arthrodesis, measuring fusion rates.	BMP-2 achieved a significantly higher fusion rate than autografts, with lower donor site morbidity and better functional outcomes.
Feng *et al.*, 2019	Patients undergoing minimally invasive lumbar fusion	Observational study analyzing clinical and radiographic outcomes in patients undergoing lumbar fusion with Infuse Bone Graft.	Infuse Bone Graft demonstrated improved fusion rates and a lower incidence of complications compared to conventional lumbar fusion techniques.
Friedlaender *et al.*, 2001	Patients with tibial nonunion treated with BMP-7	Clinical trial evaluating BMP-7's effectiveness in treating tibial nonunion, measuring bone consolidation through imaging.	BMP-7 proved effective in bone consolidation, offering a viable alternative to conventional treatments.
Glassman *et al.*, 2008	Patients undergoing lumbar fusion with Infuse Bone Graft	An observational study analyzing clinical and radiographic outcomes in patients undergoing lumbar fusion with Infuse Bone Graft	Infuse Bone Graft demonstrated improved fusion rates and a lower incidence of complications compared to conventional lumbar fusion techniques.
Ohtori *et al.*, 2013	Postmenopausal patients with accelerated lumbar fusion	Clinical trial evaluating the effect of teriparatide on accelerating spinal fusion in postmenopausal patients with osteoporosis.	Teriparatide accelerated spinal fusion in postmenopausal patients, reducing consolidation time and improving graft bone quality.

Continued

Ohtori *et al.*, 2012	Comparison of teriparatide and bisphosphonates in fusion	Comparative clinical trial between teriparatide and bisphosphonates in patients undergoing lumbar fusion, evaluating bone consolidation rates.	Teriparatide showed better results than bisphosphonates in terms of bone consolidation and functional recovery in spinal fusion patients.
Park *et al.*, 2013	Patients undergoing lumbar fusion treated with zoledronic acid	Clinical trial on patients undergoing lumbar fusion analyzed the effect of zoledronic acid on graft bone density and consolidation.	Zoledronic acid increased graft density by 20% and reduced the incidence of pseudoarthrosis. No specific complications were detailed.
Vaccaro *et al.*, 2005	Patients with lumbar fusion using OP-1 vs. autograft	Randomized clinical trial comparing OP-1 Putty (rhBMP-7) with autograft in spinal fusion, evaluating fusion rates and complications.	OP-1 achieved fusion rates comparable to autografts, with the advantage of avoiding donor site morbidity and showing good functional outcomes.
Vaccaro & Kepler, 2011	Review on spinal fusion biology	Systematic review on the principles of bone biology in spinal arthrodesis, emphasizing osteogenic, osteoinductive, and osteoconductive factors.	Analyzed three groups: DBM with bone marrow aspirate (BMA), DBM with iliac crest autograft, and autograft alone. All three groups achieved similar fusion rates, with comparable clinical outcomes and no significant complications associated with the osteobiological material.

5. Discussion

The review identified various bone grafts and biomaterials used in spinal arthrodesis, including autografts, allografts, demineralized bone matrices (DBM), bone morphogenetic proteins (BMP-2 and BMP-7), and synthetic ceramic grafts. Autografts remain the gold standard due to their osteogenic, osteoconductive, and osteoinductive properties. However, their use is limited by donor site morbidity, reported in up to 25% of cases [3] [4], and limited graft availability. In contrast, allografts, which primarily exhibit osteoconductive properties, have demonstrated fusion rates ranging from 60% to 80%. However, their lower osteogenic capacity may contribute to a slower and less robust fusion process [5]. This discrepancy underscores the need for adjunctive therapies, such as bone marrow aspirate or growth factors, to enhance the biological potential of allografts.

BMPs, particularly BMP-2, have shown promising results with fusion rates exceeding 85%, reaching up to 92% in some clinical trials [6] [7]. Their potent osteoinductive capability makes them a viable alternative to autografts, especially in patients at high risk for pseudoarthrosis. However, their use is not without concerns. Reports indicate that 10% to 20% of patients experience adverse effects, including ectopic bone formation, inflammatory reactions, and excessive bone overgrowth, which can lead to complications such as foraminal stenosis and radiculopathy [8] [9]. These findings suggest that while BMPs are a powerful tool in spinal fusion, their application should be tailored to specific patient populations, balancing benefits with potential adverse effects.

In optimizing spinal fusion outcomes, studies highlight that integrating osteobiological materials with internal fixation enhances fusion rates and reduces bone

resorption [1] [10]. Pharmacological agents like teriparatide have been particularly effective in osteoporotic patients, accelerating bone consolidation and increasing fusion rates by up to 30% compared to bisphosphonates [11]. Similarly, zoledronic acid has demonstrated efficacy in improving graft density by 20%, leading to a lower incidence of pseudoarthrosis [11] [13]. These findings emphasize the potential role of targeted bone metabolism modulation in enhancing fusion outcomes, warranting further exploration of anabolic and anti-resorptive therapies in spinal arthrodesis.

From a mechanical standpoint, instrumentation with pedicle screws has achieved fusion success rates exceeding 90%, providing significantly greater biomechanical stability than non-instrumented techniques. However, implant-related complications, such as screw loosening or migration, have been reported in 5% to 10% of cases [14]. These complications highlight the necessity of proper recipient site preparation, optimal screw placement, and the use of advanced fixation materials [15], particularly in osteoporotic patients. Emerging technologies, including expandable screws and bioactive coatings, may further enhance fixation stability and should be investigated in future studies.

Considerations for Future Research

The heterogeneity of the reviewed studies, particularly regarding patient demographics, surgical techniques, graft selection, and follow-up duration, presents a challenge in drawing generalized conclusions about the effectiveness of osteobiological materials in spinal arthrodesis. The wide variability in reported fusion rates, ranging from 60% in allografts to over 92% with BMP-2 [6] [7], suggests that patient-specific factors—such as bone density, comorbidities, and metabolic activity—play a crucial role in fusion success. Standardizing outcome measures and employing more rigorous methodologies in future research would help clarify the true efficacy of these biomaterials.

Comparing these findings with other systematic reviews reveals similar trends. Prior meta-analyses have confirmed the superior fusion rates of BMP-2 compared to traditional autografts, though with increased complication rates [16]. Additionally, studies have reinforced the importance of combining osteobiologics with mechanical stabilization [17], particularly in patients with osteoporosis or undergoing revision surgeries [18]. Future research should focus on refining patient selection criteria for osteobiologic applications, investigating novel biomaterials with enhanced safety profiles, and exploring personalized fusion strategies that integrate pharmacological and mechanical optimization.

Ultimately, this review highlights the need for a multidisciplinary approach in spinal arthrodesis, where graft selection, fixation techniques, and metabolic interventions are tailored to individual patient needs. By advancing our understanding of osteobiology and improving biomaterial technology, future innovations may further optimize fusion rates while minimizing complications [19] [20], thereby enhancing patient outcomes in spinal surgery.

6. Conclusions

In conclusion, this systematic review demonstrates that selecting the appropriate bone graft and biomaterial is fundamental to the success of spinal arthrodesis, considering their osteogenic, osteoinductive, and osteoconductive properties. While autografts remain the gold standard, alternatives such as bone morphogenetic proteins (BMP-2 and BMP-7) have shown fusion rates exceeding 85%, although they are associated with certain risks. Combining grafts with internal fixation has optimized osteointegration, achieving success rates above 90%. This highlights the importance of recipient site preparation and using biomaterials such as zoledronic acid and teriparatide in osteoporotic patients. Evidence supports implementing personalized strategies based on patient-specific conditions, minimizing complications and improving clinical outcomes. Therefore, it is essential for neurosurgeons to integrate the latest advances in osteobiology and fixation techniques to optimize spinal arthrodesis, ensuring optimal functional recovery and reducing postoperative complications.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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