

Innovative Developments in Lumbar Interbody Cage Materials and Design: A Comprehensive Narrative Review

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This narrative review comprehensively examines the evolution and current state of the interbody cage technology for lumbar interbody fusion (LIF). This review highlights the biomechanical and clinical implications of transition from traditional static cage designs to advanced expandable variants for spinal surgery. The review begins by exploring the early developments in cage materials, highlighting the roles of titanium and polyetheretherketone in advancing LIF techniques. It discusses the strengths and limitations of these materials, leading to innovations in surface modifications and the introduction of novel materials, such as tantalum, as an alternative material. Advancements in three-dimensional printing and surface modification technologies form a significant part of this review, emphasizing the role of these technologies in enhancing the biomechanical compatibility and osseointegration of interbody cages. This review also explores the rise of biodegradable and composite materials such as polylactic acid and polycaprolactone, addressing their potential to mitigate long-term implant-related complications. A critical evaluation of static and expandable cages is presented in this review, including their respective clinical and radiological outcomes. While static cages have been a mainstay of LIF, expandable cages are noted for their ability to adapt to the patient's anatomy, potentially reducing complications such as cage subsidence. However, this review highlights the ongoing debate and the lack of conclusive evidence regarding the superiority of either cage type in terms of clinical outcomes. Finally, this review proposes future directions for cage technology, focusing on the integration of bioactive substances and multifunctional coatings and development of patient-specific implants. These advancements aim to further enhance the efficacy, safety, and personalized approach of spinal fusion surgeries. This review offers a nuanced understanding of the evolving landscape of cage technology in LIF and provides insights into the current practices and future possibilities in spinal surgery.

Keywords: Lumbar interbody fusion; Spinal surgery

Introduction

Lumbar interbody fusion (LIF) has emerged as a pivotal technique for managing various spinal pathologies, from

degenerative disc disease to spondylolisthesis and spinal instabilities [1]. The clinical relevance of LIF lies in its ability to restore spinal alignment, relieve neurological symptoms, and provide long-term stability, representing

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significant advancement in spinal surgery. The evolution of this procedure reflects the continual search for optimal patient outcomes by balancing surgical invasiveness with efficacy [2].

The efficacy of LIF is significantly influenced by the choice of interbody cages, which have evolved based on the advancement of biomaterial science. Various biomaterials are utilized in interbody cage development, from traditional materials, such as titanium (Ti) and polyetheretherketone (PEEK), to newer materials, such as tantalum. Three dimensional- (3D) printing technologies and surface modifications using plasma-spraying technology have taken interbody cage development to the next level [3]. These developments highlight the synergistic relationship between surgical techniques and biomaterials science, which is crucial for improving the outcomes of LIF. More recently, the introduction of biodegradable materials and the development of the expandable cage technique have further expanded the world of interbody cages.

Despite extensive research and clinical applications of various cages in LIF, gaps remain in understanding the comprehensive impact of cage design and material on patient outcomes. Previous studies have often focused on isolated aspects of cage performance, such as subsidence rates or fusion efficacy, without a holistic view of how these factors interact with overall spinal biomechanics and long-term outcomes [4]. Additionally, there is a lack of consensus regarding the optimal cage type for specific clinical scenarios, highlighting the need for a more nuanced understanding. This narrative review aims to bridge these gaps by providing a comprehensive overview of the evolution of cage designs and materials in LIF and critically evaluating their clinical implications, focusing on identifying areas for future research and innovation.

Evolution of Cage Materials in LIF

1. Early developments and traditional materials

1) Titanium

The evolution of the LIF cages began with the development of simple materials and techniques. Earlier cages, primarily composed of stainless steel and Ti, were designed to provide mechanical stability and facilitate bone grafting procedures [5]. These materials were chosen for their strength and biocompatibility, although challenges such as stress shielding and radiopacity were noted. The

use of cages in spinal procedures was pioneered in the early 1980s, marking a significant shift from traditional bone grafting methods [6,7].

Ti and its alloys soon became the primary choice for cage fabrication because of their favorable properties, including biocompatibility and the ability to promote bone ingrowth. Ti6Al4V is typically chosen for interbody cage production because of its strength, corrosion resistance, low density, biocompatibility, cost-effectiveness, and magnetic resonance imaging compatibility [8-10]. Advancements in the design and application of Ti cages in the 1990s and early 2000s led to various configurations, such as cylindrical and box-shaped designs, to improve fusion rates and reduce complications, such as cage migration or subsidence [7,11].

Despite their widespread use, Ti present certain challenges. For instance, the mismatch in the elastic modulus between Ti cages and native bone leads to concerns about stress shielding, potentially affecting the long-term stability and integration of the implant. Seaman et al. highlighted that the high elastic modulus of Ti6Al4V can lead to cage subsidence and loss of disc height restoration [12]. Additionally, the radiopaque nature of Ti hinders the precise assessment of fusion progression using imaging techniques, prompting the exploration of alternative materials [13]. Recent advancements in 3D-printing and surface treatment technologies have enabled the creation of 3D-printed Ti interbody devices with elastic moduli comparable to native bone [14-16].

2) Polyetheretherketone

The introduction of PEEK has significantly altered the landscape of cage materials used for lumbar fusion surgery. PEEK is known for its biomechanical compatibility with bone, characterized by an elastic modulus that closely mirrors that of cortical bone and its radiolucency, which facilitates postoperative imaging [17-19]. Clinical comparisons between PEEK and Ti cages have yielded inconclusive results regarding superiority, with each material exhibiting distinct advantages and disadvantages [12,20]. Compared with Ti alloys, PEEK reduces stress shielding and bone resorption, mitigating implant loosening risks [21,22]. A meta-analysis by Seaman et al. (2017) revealed comparable fusion rates between Ti and PEEK interbody cages yet highlighted a 3.59-fold higher subsidence likelihood with Ti [12]. Consequently, from the perspective of subsidence and stress shielding, PEEK appears

to offer advantages over Ti.

However, PEEK's hydrophobic characteristics and bioinertness may impede its osteointegration [23]. Furthermore, biofilm formation on PEEK surfaces impedes binding to the host bone, thereby hindering solid fusion [24]. PEEK cages have also been associated with local inflammation, potentially leading to complications such as bone nonunion and osteolysis [20,25,26]. Efforts to address these shortcomings have led to surface modification of PEEK to enhance its bioactivity. [27-29].

3) Tantalum

Tantalum, increasingly utilized in orthopedics due to its excellent histocompatibility and corrosion resistance, shows promise as an interbody fusion cage biomaterial [30-32]. Tantalum and its derivatives surpass Ti and its alloys in terms of mechanical strength, corrosion resistance, and biocompatibility [33-37]. Tantalum exhibits superior osseointegration and antibacterial properties. Porous tantalum has garnered significant interest among its derivatives due to its elastic modulus and porous architecture, which closely resembles cancellous bone [38]. Currently, Ta and its derivatives are effectively employed in artificial joint replacements [39], treatment of femoral head necro-

sis [40], and dental material applications [41], benefiting a wide patient population. In spinal surgery, the application of tantalum extends to treating infectious bone defects and anterior cervical discectomy and fusion [42-46] (Fig. 1).

Clinical results from various studies have demonstrated that porous tantalum cages (PTCs) are effective and safe for spinal surgery, offering several advantages. In anterior lumbar interbody fusion (ALIF), PTCs significantly improve lumbar lordosis (LL), reduce back pain, and enhance the quality of life without major complications [47]. Thoracolumbar burst fractures provide superior sagittal profile restoration compared to iliac crest bone grafts, with a lower tendency for correction loss over time [48]. This suggests that PTCs could be a viable alternative to autologous bone grafting, potentially avoiding donor-site morbidity. Furthermore, in posterior lumbar interbody fusion (PLIF), PTCs show promising results in early bone integration and stability, as indicated by computed tomography findings of trabecular bone remodeling and lower incidences of vertebral endplate cyst formation compared with Ti-coated PEEK (Ti-PEEK) cages [49]. Collectively, these studies suggest that PTCs can achieve immediate stabilization, facilitate bone fusion, and improve long-term outcomes in spinal surgery.

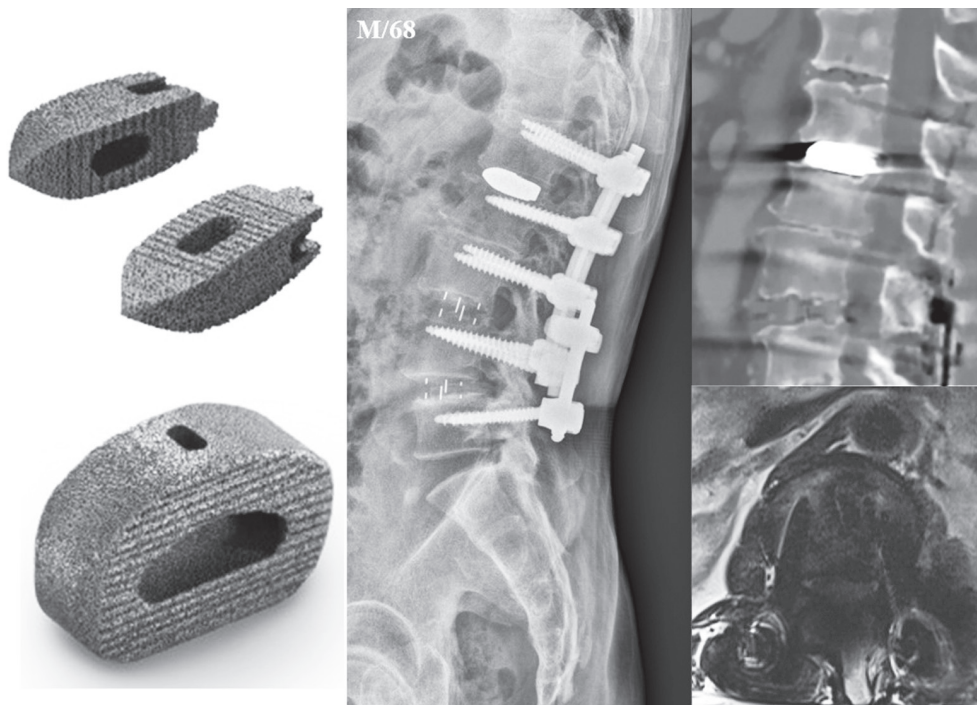


Fig. 1. Examples of tantalum cages. Representative cases illustrate the application of tantalum cages, such as in a 68-year-old male patient where a tantalum cage was placed in the L1-2 intervertebral space, resulting in artifact generation on postoperative CT and MRI.

2. Advancements in 3D-printing and Surface Modification

1) 3D-printing Technology

The emergence of 3D-printing technology in spinal cage production marks a pivotal development, allowing the creation of patient-specific implants with intricate, customizable porous structures [50]. This technology has opened new avenues for designing cages that promote bone ingrowth and vascularization, potentially optimizing the fusion process [51,52]. By utilizing materials such as Ti, 3D-printed structures offer a harmonious blend of mechanical resilience and biological functionality, demonstrating the potential to enhance osseointegration and reduce the risk of non-device-related reoperation [53-55]. For example, a 3D-printing features an elastic modulus closely matching that of the native bone, while a conventional titanium alloy cage has an approximately 10-folds higher elastic modulus [14-16].

The biomechanical superiority of these 3D-printed cages has led to favorable results in previous clinical studies. Amini et al. showed that in patients with stand-alone lateral lumbar interbody fusion (LLIF) patients, 3D-printed Ti cages exhibited a significantly lower early subsidence rate than PEEK cages [56]. Corso et al. analyzed 186 patients (50.5% male, mean age 59.2 ± 12.5 years) with a minimum follow-up of 6 months. Of these, 96 were treated with 3D-printed Ti implants and 90 with PEEK across 186 implant levels, of which 51.6% utilized 3D-printed Ti implants [54]. They concluded that, in terms of non-device-related reoperation events, 3D-printed Ti cages demonstrated a minimal risk profile compared with traditional non-3D printed cages. Yang et al. reviewed 150 patients who underwent 1-to 2-level PLIF with a minimum follow-up of 2 years. The results indicated that 3D-printed Ti cages achieved significantly higher fusion rates at both 1 (3D-printed Ti, 86.9%; PEEK, 67.7%; $p=0.002$) and 2 years (3D-printed Ti, 92.9%; PEEK, 82.3%; $p=0.037$) postoperatively than the PEEK cages [57]. There was no significant difference in subsidence rates between the two materials. These results suggests that 3D-printed Ti cages are a viable and safe option for PLIF because they provide a stable construct.

2) Surface modifications

The surface properties of the interbody cages significantly affect osteointegration. Enhanced surface porosity promotes osteointegration by increasing the surface area

and incorporating osteogenic and angiogenic factors such as BMP-2 [58]. Previous studies have demonstrated the clinical and radiological advantages of these surface-modified interbody cages. Guyer et al. found that porous Ti exhibits a stronger implant-bone interface than the conventional PEEK and allografts, indicating its superior potential for osseointegration and faster achievement of spinal fusion stability [59].

As for the porous PEEK cages, Torstrick et al. examined the effects of porosity and pore size on the cellular responses to PEEK using micro-CT analysis. They discovered that porous PEEK exhibited increased cell proliferation and cell-mediated mineralization compared with smooth PEEK and Ti [60]. Furthermore, to address PEEK's inherent hydrophobicity and bioinertness of PEEK, surface modifications incorporating materials such as hydroxyapatite (HA), calcium silicate (CS), and Ti have been explored to augment PEEK's bioactivity [27-29,61]. Sun et al. investigated the integration of soft tissues with HA/PEEK composite scaffolds. The results showed that although the overall bonding strength was influenced mainly by pore size rather than HA content, HA played a significant role in enhancing the firm adhesion of soft tissue to PEEK-based composites, a key factor in preventing postoperative effusion [61].

As for the CS/PEEK cages, Chu et al. demonstrated in a goat cervical interbody fusion model that CS/PEEK cages outperformed pure PEEK cages in terms of fusion strength at 12 and 26 weeks, as evidenced by X-ray analysis. Micro-computed tomography revealed greater new bone ingrowth with CS/PEEK cages, achieving near-complete fusion at 26 weeks. Additionally, these cages exhibited superior mechanical stability and stiffness, as confirmed by spine kinematics assays. Histological evaluations have highlighted rapid osseointegration and bone formation around the CS/PEEK cages [21].

Regarding the Ti-PEEK cage, Zhu et al. reported that PEEK cages with Ti and HA coatings, in contrast to uncoated PEEK cages, achieved a significantly higher fusion rate three months after single-level transforaminal lumbar interbody fusion (TLIF) [62]. Two recent meta-analyses comparing Ti-PEEK cages with uncoated PEEK cages in lumbar fusion surgeries found comparable effects on bone fusion and cage subsidence across all follow-up periods, indicating no significant differences in patient-reported outcomes [27,28]. However, Ti-PEEK cages offer the combined benefits of Ti and PEEK: an elastic modulus

akin to that of human cortical bone, enhanced osteoid cell growth, and increased cell adhesion space.

Torstrick et al. demonstrated that the microstructure of surface-coated PEEK, including its pore morphology, can be precisely manipulated by varying the size of the sodium chloride crystals, with pores adopting the cubic shape of the porogen. Their findings suggested that introducing a porous surface layer to polymeric implants can enhance clinical outcomes while preserving a sufficient load-bearing capacity [63]. There are concerns regarding the durability and impaction resistance of the coatings, mainly because of the substantial impact forces encountered during the insertion of cages into the intervertebral space. Torstrick et al. also showed that while porous PEEK devices sustained minimal damage during aggressive cervical impaction, devices with Ti-PEEK experienced a significant loss in their initial Ti coverage [60].

3. Biodegradable and composite materials

Recent advancements have also led to the rise of biodegradable materials, such as polylactic acid (PLA) and polycaprolactone (PCL), in fabricating spinal cages. These materials are designed to degrade over time, ideally replaced by natural bone, thus mitigating long-term complications associated with permanent implants [64,65]. Although initial applications face challenges related to mechanical integrity and controlled degradation, recent iterations have shown promising outcomes. This is particularly evident when these materials are used in conjunction with osteoconductive or osteoinductive substances to enhance the process of spinal fusion [66,67]. The evolution of biodegradable cages continues to be a central theme in spinal surgery research, focusing on optimizing their composition and structure to improve clinical outcomes. Biodegradable materials such as PLA and PCL are at the forefront of this innovation due to their ability to reduce long-term complications associated with traditional implants [3,64,65,68].

1) Polylactic acid

The primary polymers used were PLA and PCL, which are Food and Drug Administration-approved polyesters. The formation of block copolymers such as poly L-lactic acid (PLLA), poly-D, L-lactic acid, and poly(lactic-co-glycolic acid) (PLGA) is achieved through the covalent bonding of different polymer units. Among these, aliphatic polyesters,

particularly PLAs, are the most promising category [69-71]. Previous studies have confirmed the biocompatibility of PLA with dural and neural tissues, and further research has indicated that PLA has no detrimental effects on neuronal cells or pH alterations during PLA implant degradation at the implantation site [72-75].

Despite their theoretical advantages, a systematic review focused on biodegradable implants, predominantly polylactides, and their comparison with conventional implants showed that the routine clinical application of absorbable cages lacks sufficient support, primarily because of unfavorable long-term fusion rates [76]. The inferior clinical outcomes of biodegradable cages are hypothesized to arise from early degradation and strength loss, leading to osteolysis and accelerated cage subsidence [77,78].

2) Polycaprolactone

In contrast to PLA, which is a bulk-degrading polymer [79], PCL is bioerodible and maintains its initial elastic modulus and 95% mass for up to 12 months [80]. Owing to its superior rheological and viscoelastic properties compared to other aliphatic polyesters such as PLLA, poly-L-lactide-co-D, and L-lactide acid [81], PCL is a promising candidate for designing slow-degrading implants, mainly because of its favorable melt extrusion properties. PCL is distinguished by its superior physicochemical properties, such as structural stability [82], flexibility [83], biocompatibility [84], and biodegradability [85]. In vivo, PCL demonstrates slow degradation, with virtually no molecular weight changes observed after six months [86]. It exhibits greater resistance to degradation in biofluids than other polymers, and its low cost and accessibility add to its advantages [87,88]. Moreover, PCL enhances cell viability and migration more effectively than rapidly degradable PLGA-3D scaffolds, as demonstrated in both in vitro and in vivo studies [89]. Coinciding with advancements in additive biomanufacturing, PCL has gained prominence and become increasingly preferred for fabricating biodegradable cages for spinal fusion.

In multiple large preclinical animal studies, a composite of PCL with ceramics, specifically calcium phosphate (CaP), has emerged as the optimal biomaterial for osseous healing in critical-size tibial defects [90,91]. This combination results in composite biomaterials that offer improved mechanical properties, controlled degradation rates, and enhanced bioactivity, making them well-suited for bone tissue engineering applications [92,93]. Bioactive

and bioresorbable scaffolds, made from medical-grade PCL with 20% β -tricalcium phosphate incorporation and bioresorbable PCL scaffolds coated with a biomimetic CaP layer plus recombinant human bone morphogenetic protein-2 (rhBMP-2), have been effectively utilized to attain interbody spinal fusion in both lumbar porcine and thoracic ovine models [66,94]. Li et al. noted that autograft-free biodegradable PCL-TCP composite scaffolds facilitated bone tissue ingrowth and maintained mechanical load-bearing capacity post-implantation, achieving a spinal fusion efficacy comparable to that of Ti cages with autografts in sheep anterior cervical discectomy and fusion surgeries [95]. However, similar to PLA, PCL faces the challenge of inferior mechanical properties compared to permanent materials such as Ti and PEEK. This performance gap becomes more evident as degradation occurs, potentially resulting in reduced stability over time.

3) Future of biodegradable materials

The final goal is to develop cages that offer the best strength and durability with eventual resorption and replacement by natural bone. The key focus areas include addressing issues such as premature degradation and ensuring adequate mechanical support during the critical bone healing and fusion period. Research is geared towards developing materials with optimized degradation rates, improved mechanical strength, and enhanced bioactivity to support the spine until complete osseointegration is achieved. Regarding mechanical strength, improving the stiffness of PCL scaffolds can be achieved by increasing their mineral content, particularly with HA. Shor et al. demonstrated that adding 25% HA to a composite resulted in a 40% increase in the compressive modulus [96]. Furthermore, the stiffness of the PCL/HA mixture increases proportionally with the HA content [97].

The unmodified PCL surfaces exhibited limited cell adhesion, attachment, proliferation, and bioactivity. Applying nano-HA coatings, a type of CaP with a composition and crystal structure akin to human bone may enhance cytocompatibility [98]. Yong's study indicates that a CaP-coated PCL-based scaffold with 0.54 μ g rhBMP-2 is as effective as an autograft from the rib head. This created a conducive environment for thoracic interbody spinal fusion in the sheep thoracic spine model [99]. Recently, Duarte et al. showcased a novel biopolymer of polycaprolactone doped with polydopamine and polymethacrylic acid, which, when foamed directly into a bone defect through a special-

ized high-pressure portable device, achieved immediate stabilization of osseous components [100]. This technique yields a 3D structure with morphological properties similar to those of the trabecular bone, showing significant potential for instrumentation-free interbody fusion.

4. Static vs. expandable cages in LIF

1) Static cages

Static cages, predominantly used in LIF, are pivotal in addressing degenerative spinal disorders [101,102]. The evolution of interbody fusion cages from the earliest threaded BAK designs to the current Ti or PEEK cages has led to shapes more closely resembling intervertebral space. This design shift offers larger cancellous bone-filling spaces, increased fusion area, enhanced load-bearing capacity, and improved stability. These cages, characterized by their fixed shape and size, are designed for strength and ease of insertion, crucial elements in lumbar surgery. Their simple and robust design provides reliable support to the spinal segment, ensuring a consistent approach for various lumbar pathologies [20,103-105].

Recently, there has been a growing emphasis among physicians and patients on minimally invasive surgical techniques for implanting the largest feasible intervertebral implant through the smallest possible incision with minimal surgical exposure. The anterior approach facilitates the use of larger bone cages and grafts than the posterior approach, demonstrating enhanced deformity correction capabilities and superior initial stability [106-108]. Over the last 50 years, significant advancements in surgical methods and instrumentation for ALIF and LLIF have been observed. Critical factors, such as cage dimensions, including width, length, height, and contact surface area, are pivotal in maximizing surface contact and ensuring the stability of ALIF and LLIF [102]. Radiologically, static cages have been instrumental in achieving the desired outcomes in spinal surgeries. Research has indicated their efficacy in restoring and maintaining segmental lordosis (SL) and disc height, which are critical for preserving the natural curvature and biomechanics of the spine [109-111].

Recent developments in endoscopy-assisted spine fusion surgeries have demonstrated clinical and radiological outcomes comparable to conventional open surgery [112-115], thus emphasizing the need for specialized cage designs suitable for minimal incision techniques. Kim et

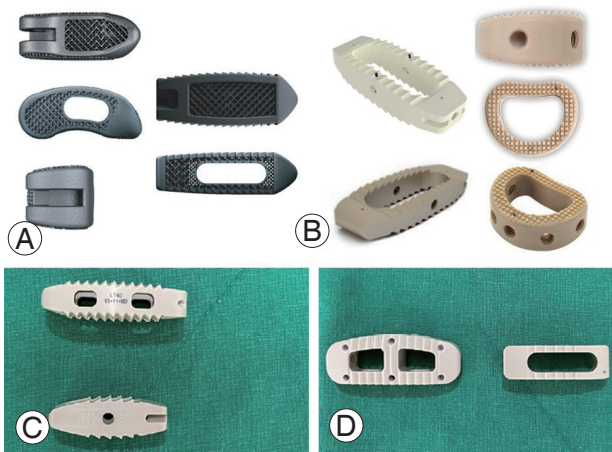


Fig. 2. The lumbar interbody cages vary in design and size. (A) A titanium cage suitable for TLIF and PLIF, (B) A larger PEEK cage designed for OLIF, LLIF, or ALIF. Views (C) and (D) present lateral and axial perspectives of two distinct cages. The larger cage measures 15 mm in width and 40 mm in length, making it suitable for endoscopic transforaminal lumbar interbody fusion, while the smaller cage's dimensions are 10 mm by 32 mm. These figures are presented with permission from the authors (Kim JE et al., *World Neurosurgery*, 2023).

al. recently demonstrated the feasibility of using a larger cage originally designed for LLIF in biportal endoscopic TLIF to achieve a favorable fusion rate [116] (Fig. 2). With the increasing adoption of minimally invasive techniques, technological advancements have led to the development of interbody devices designed to expand after placement.

2) Expandable cages

Unlike static devices, expandable cages are designed for insertion with a minimal profile and can be expanded in situ to reduce iatrogenic endplate damage during cage insertion [117]. The cages were designed to adjust their size and shape to conform to the unique anatomical needs of the patient's intervertebral space. Their ability to expand post-insertion allows for a customized fit and enhanced spinal stabilization, significantly evolving from traditional static cage designs.

Expandable cages can be used for TLIF, ALIF, and LLIF [118]. Although TLIF is a procedure in which expandable cages were initially implemented [119], this procedure can be limited to cases with extensive scarring and high-grade spondylolisthesis [4]. Meanwhile, ALIF and LLIF allow the insertion of wide and large interbody cages, resulting in a greater endplate contact surface than TLIF cages [111]. However, implanting such large cages often requires strong impaction when static cages are used. In contrast, expandable LLIF cages obviate the need for the

forceful impaction associated with static spacers, thereby potentially reducing the risk of cage subsidence [118].

From the radiological perspective, the use of expandable cages in lumbar fusion has yielded promising results. Expandable cages have been reported to yield superior disc height increments and SL restorations in lumbar fusion patients compared with static cages [120-124]. Research indicates that these cages effectively maintain or improve the SL and disc height, which are critical factors in achieving optimal spinal alignment and biomechanics after surgery. Recent meta-analyses indicate that the design of expandable cages plays a key role in reducing the incidence of cage subsidence in lateral interbody fusion, a frequent complication in lateral lumbar surgeries, thus helping to maintain the structural integrity of the fused spinal segment [125] (Fig. 3).

3) Comparative studies and current evidence

It remains unclear whether expandable cages are associated with improved clinical outcomes in patients with lumbar fusion compared with static cages [125-128]. Three recent meta-analyses assessing the clinical outcomes of expandable cages in TLIF revealed no significant differences in Visual Analog Scale scores for back and leg pain, Oswestry Disability Index (ODI), and fusion rates between static and expandable cages. [126-128]. Another meta-analysis evaluating clinical outcomes of expandable cages in both TLIF and PLIF found no significant differences in ODI, fusion rates, LL, blood loss, and operation time when comparing the use of static versus expandable cages [125]. However, the meta-analysis above documented the role of expandable cages in reducing operative time and intraoperative blood loss, thereby contributing to faster patient recovery and reduced hospital stays [126]. These findings indicate the potential of expandable cages to enhance patient comfort and accelerate postsurgical rehabilitation and recovery.

In terms of radiological outcomes, expandable cages can achieve superior disc height increments and SL restoration in lumbar fusion patients compared to static cages. [120-124,126,127]. However, a meta-analysis focusing on the radiological outcomes of TLIF revealed no statistically significant differences in the spinal sagittal alignment (SL and LL) or pelvic parameters [127]. Concurrently, expandable cages have been linked to a reduced incidence of subsidence, as evidenced in previous studies [121-123,129,130]. This reduction may be attributed to their

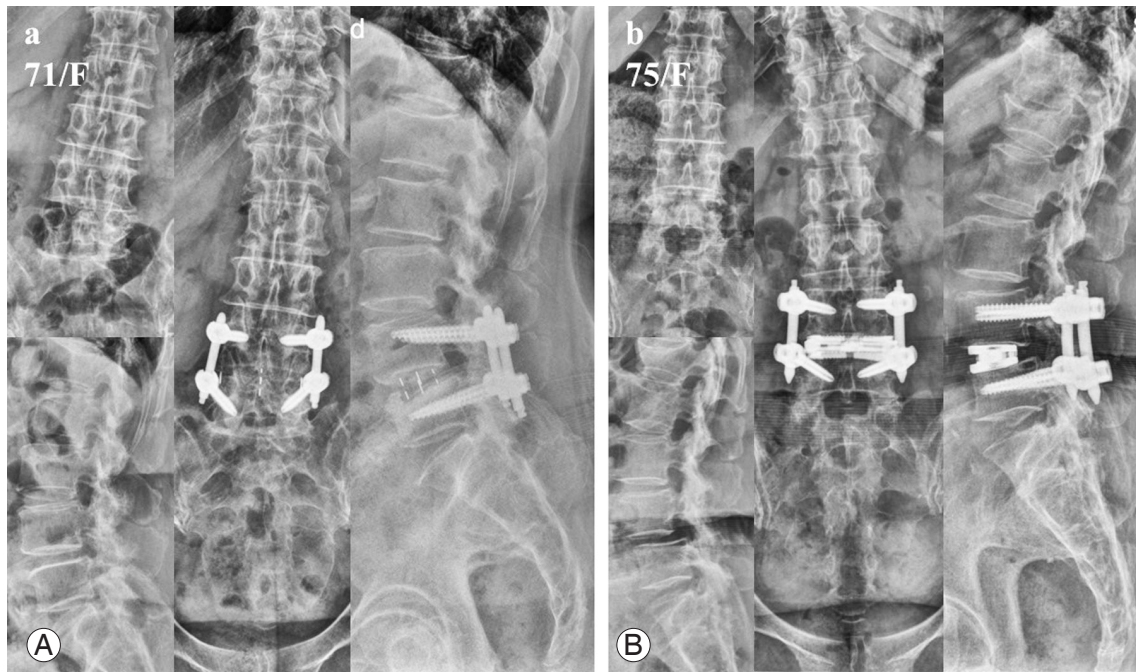


Fig. 3. (A) A 71-year-old female patient underwent L4-5 OLIF with a static PEEK cage and exhibited cage subsidence in the 3-month postoperative follow-up X-ray. (B) A 75-year-old female patient received L4-5 OLIF with an expandable cage and has sustained proper alignment without any signs of cage subsidence for 3 months.

capacity to attain a tailored fit within the intervertebral space. However, two recent meta-analyses focusing on expandable TLIF cages did not demonstrate any significant difference in cage subsidence between static and expandable cage usage [126,127]. Frisch et al. and Li et al. reported that expandable LLIF cages resulted in an expandable group with a significantly lower subsidence rate [117,131,132]. They also reported increased postoperative disc space measurements compared with preoperative levels, noting a statistically more significant change in static cages than in expandable cages [117,131,132]. This difference may be due to the over-distraction required for static cage insertion. Consequently, an expandable LLIF cage that avoids forceful insertion may play a role in preventing subsidence. Further research is needed to ascertain whether expandable cages exhibited variability in their subsidence prevention efficacy based on the surgical technique employed and to understand the underlying reasons for such differences.

The association between expandable cages and improved clinical outcomes in patients with lumbar fusion compared to fixed cages remains uncertain. Expandable cages have several advantages in certain aspects. Therefore, choosing between static and expandable cages should be based on patient-specific factors and surgical

objectives. Surgeons need to weigh these findings against individual patient needs, surgical goals, and the specific pathology being addressed to choose the most appropriate interbody device.

4) Future directions in cage technology for LIF

As technology continues to evolve, future research should explore the integration of bioactive substances into 3D-printed cages. Embedding growth factors or osteoinductive materials within the scaffold structure could further promote bone growth and fusion [133,134]. In addition, ongoing advancements in materials science may introduce new biocompatible materials that enhance the functionality of 3D-printed cages. The combination of customizable design, improved material properties, and the integration of bioactive agents is poised to significantly advance the efficacy and safety of LIF procedures, paving the way for more personalized and effective spinal treatments.

Research has been increasingly focused on multifunctional coatings that combine osteoinductive properties with antibacterial capabilities. The development of dual-function coatings could revolutionize LIF procedures by enhancing bone growth and reducing the risks [135]. Future studies must explore incorporating novel materials and bioactive agents into these coatings, potentially lead-

ing to even greater improvements in clinical outcomes. As this field evolves, the focus will likely shift towards customizing coatings based on specific patient needs and surgical context, further personalizing LIF treatments and improving patient-specific outcomes.

The future of LIF is likely to be shaped by continuous innovations in material science and technology. Research has focused on developing materials directly delivering targeted therapeutic agents, such as growth factors or antibiotics, to the fusion site [20]. Additionally, the exploration of personalized implants tailored to each patient's specific anatomical and pathological conditions represents a significant advancement in patient-specific care. These emerging materials and technologies have the potential to significantly improve the efficacy, safety, and patient outcomes of spinal fusion surgeries, marking a new era in the treatment of spinal disorders.

Conclusions

In conclusion, the dynamic evolution of cage technology in LIF represents a significant advancement in managing spinal disorders, offering spine surgeons diverse tools tailored to optimize patient outcomes. The transition from traditional materials to innovative synthetic, biodegradable, and composite materials reflects a deeper understanding of biomechanics and materials science. Advancements in 3D printing and customizable solutions have ushered in an era of patient-specific implants, ensuring a closer match between anatomical and pathological conditions. The exploration of surface modifications, bioactive coatings, and emerging materials such as smart biomaterials signifies a paradigm shift towards implants that support structural integrity and actively participates in the biological healing process. Moreover, the development of static and expandable cages, each with distinct clinical and radiological outcomes, highlights the importance of personalized treatment strategies for spinal surgery. These technological advancements integrated with clinical expertise have the potential to enhance the efficacy, safety significantly, and overall success of spinal fusion procedures, marking a pivotal step forward in orthopedic surgery.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

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