Case Report

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3D Printed Titanium Anterior Lumbar Interbody Fusion Cage for Treatment of Foraminal Stenosis Due to Congenital L5 Hemivertebra with Virtual Surgical Planning: Technical Note and Case Report

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Abstract

The integration of three-dimensional (3D) printing and virtual surgical planning (VSP) has introduced a new standard in spinal surgery, enabling highly individualized preoperative preparation and intraoperative execution. By virtually reconstructing patient anatomy, surgeons can identify critical vascular corridors, analyze endplate morphology, determine optimal interbody cage geometry for best anatomical fit, and predefine screw trajectories and entry points with exceptional accuracy. This level of planning reduces intraoperative uncertainty and minimizes the risk of implant malposition, particularly in anatomically complex scenarios, such as the current case report. Quantitative assessment of alignment correction can also be performed preoperatively, allowing the surgeon to model and predict postoperative spinal balance with greater precision. This technology is particularly advantageous in congenital spinal anomalies, such as hemivertebrae, where orientation can be challenging and anatomical landmarks are often distorted or partially obscured. We report the application of 3D printed patient-specific implants (PSIs) in conjunction with VSP to perform a single-level, stand-alone anterior lumbar interbody fusion (ALIF) for the treatment of congenital scoliosis due to a left hemivertebra, associated with progressive left L5/S1 foraminal stenosis. The patient presented with severe left L5 radicular pain and motor–sensory radiculopathy. The use of a PSI facilitated precise reconstruction of the spinal column, optimized implant fit and enhanced surgical accuracy in this technically complex case.

Keywords: foraminal stenosis; hemivertebra; patient's specific implant (PSI); vertebral wedge deformity; anterior lumbar interbody fusion (ALIF); 3D printed interbody cage

Introduction

A hemivertebra represents a defect of embryological vertebral formation, characterised by a wedge-shaped vertebral body with a single hemi-lamina and pedicle, resulting from failure of formation of one of the two primary ossification centres [1]. With an estimated incidence of 1–10 per 10,000 live births, hemivertebrae are among the most common causes of congenital scoliosis [1–5]. Lumbar hemivertebrae occur due to maldevelopment of a single half of the vertebral body and are a well-recognised cause of spinal deformity in childhood, adolescence, and adulthood. While typically sporadic, they may also occur as part of various syndromic conditions such as Klippel–Feil, Jarcho–Levin (Spondylocostal Dysostosis), and VACTERL associations [5–8]. Coexisting congenital

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anomalies are frequent [9]. Prenatal ultrasound can sometimes identify hemivertebrae [4], but they are most commonly diagnosed during evaluation of progressive scoliosis in childhood or adulthood.

The goals of treatment include halting progression of the deformity, relieving pain, improving cosmetic alignment, removing or reconstructing the hemivertebra when indicated, decompressing neural elements, and achieving stable, durable correction in accordance with established scoliosis treatment paradigms [11,12]. Surgical strategies have traditionally relied on "subtractive" techniques, including hemivertebra resection, decortication with in-situ fusion, and osteotomies.

Recent advances in virtual surgical planning (VSP) and three-dimensional (3D) printed patient-specific implants (PSIs) have enabled more sophisticated, anatomy-tailored approaches. VSP facilitates comprehensive preoperative analysis of patient anatomy, including vascular structures, variant anatomy, endplate morphology, cage placement points, and potential osteotomy sites. It allows surgeons to virtually plan osteotomies, screw trajectories, cage dimensions, and to quantify foraminal correction achievable through interbody distraction [10,13,14]. PSIs, developed through VSP, enable accurate, reproducible implant placement while minimising the risk of intraoperative complications—particularly vascular injury—through precise approach planning. Compared with conventional subtractive methods, this approach represents a shift toward an "augmentative" paradigm, with potentially less intraoperative morbidity and improved postoperative recovery.

Anterior lumbar interbody fusion (ALIF) has emerged as an effective technique for deformity correction, indirect decompression, and sagittal balance restoration, particularly at the lumbosacral junction. The anterior approach allows for wide exposure of the disc space, placement of large lordotic implants, and correction of deformity with minimal posterior disruption. There is a wealth of evidence [15] that highlights the advantages of ALIF for lumbar pathology, including its ability to restore disc height and sagittal alignment, and its biomechanical stability when combined with appropriate instrumentation. In this report, we describe the application of VSP and 3D-printed PSIs as part of a single-level ALIF procedure to treat symptomatic degeneration and congenital scoliosis associated with a lateral L5 hemivertebra in an adult female patient. This case illustrates the utility of combining anterior-based deformity correction with modern patient-specific technologies to address complex congenital spinal pathology.

Technical Note

A 53-year-old right-handed female presented with a three-year history of left paramedian lumbosacral pain, exacerbated by prolonged standing. The back pain was rated at 6–8/10 on the Visual Analogue Scale (VAS) and had progressively interfered with activities of daily living. Over the preceding six months, she had also developed left L5-pattern sciatica with a clear mechanical and weight-bearing component. Conservative management — including temporarily effective caudal steroid injections, structured physiotherapy, multimodal pain strategies, regular analgesia, and weight loss — failed to provide sustained relief. Neurological examination demonstrated an incomplete left L5 motor radiculopathy with 4+/5 weakness in the extensor hallucis longus and foot eversion, with normal strength elsewhere. There was mild sensory loss to light touch in the left L5 dermatome, and her gait exhibited a mild Trendelenburg pattern. There were no signs of myelopathy.

Radiological assessment included standing EOS films, MRI, and CT imaging. EOS imaging (**Figure 5**) revealed both coronal and sagittal deformity. CT and MRI (**Figures 1 and 2**) confirmed a trapezoidal L5 hemivertebra and progressive severe left L5 bony foraminal stenosis. Comparison with MRI performed two years earlier demonstrated progressive narrowing of the left L5/S1 foramen (**Figure 2**).

Given the complex anatomy and anticipated challenges of anterior exposure, further evaluation with CT abdomen and dedicated vascular imaging was performed. A multidisciplinary team discussion concluded that a single-level anterior lumbar interbody fusion (ALIF) at L5/S1, with foraminal correction using a patient-specific implant (PSI), represented a targeted strategy to address both the deformity and radiculopathy. The adjacent L4/5 level was also evaluated and deemed uninvolved. Virtual surgical planning (VSP) was undertaken to analyse vascular approach anatomy, endplate morphology, optimal cage geometry, and screw entry points, and to virtually model foraminal reconstitution. A custom 3D-printed patient-specific interbody device (3DMorphic, Sydney, Australia) was manufactured. The patient underwent a single-level stand-alone L5/S1 ALIF with deformity correction and foraminal decompression. The postoperative course was uneventful, and at 3 and 12 month follow-up she demonstrated complete resolution of radicular pain and neurological deficit, with restoration of normal function and gait mechanics.

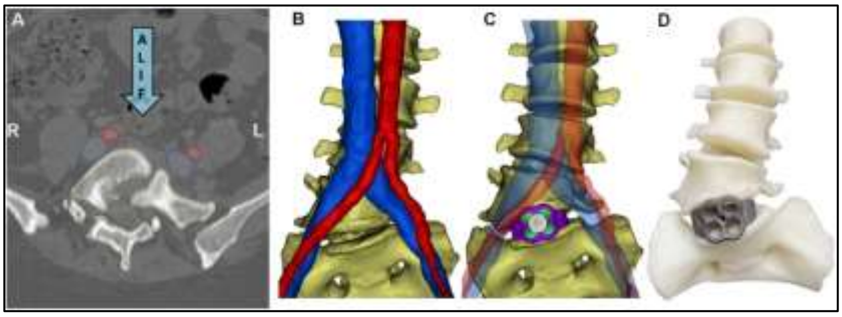

Figure 1. Illustration of Virtual Surgical Planning (VSP) with respect to the major vascular structures for an ALIF approach. (**A**) Axial CT slice with vascular structures outlined: common iliac arteries [red]; common iliac veins [blue]. (**B**) 3D model of the pathological spine osteology, also showing the major arteries (red) and veins (veins). (**C**) 3D model demonstrating planned PSI positioning relative to the major vessels, and (**D**) Anatomical biomodel showing the positioning and fit of the patient specific implant (PSI).

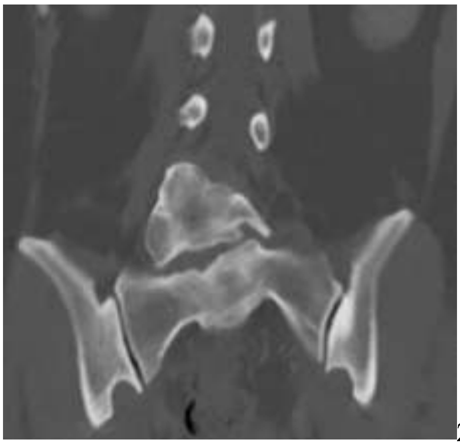
2019


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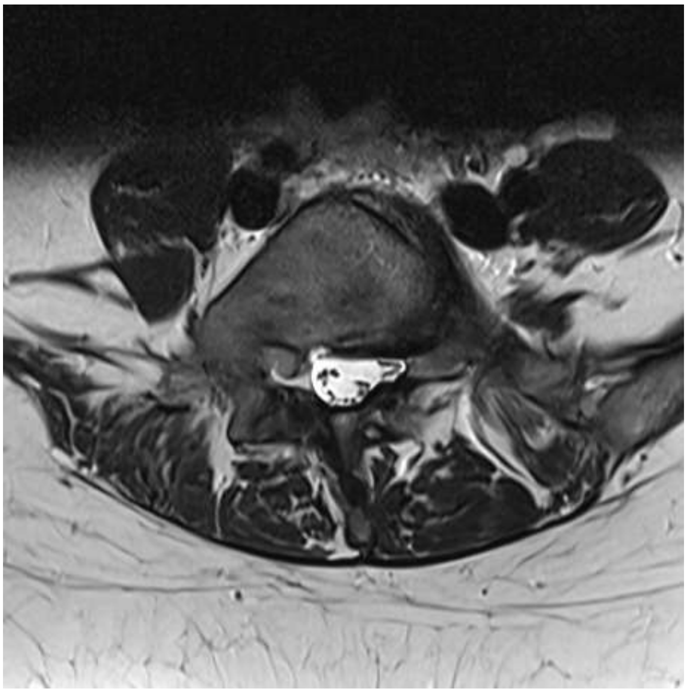
Figure 2. MRI showing progressive left L5/S1 foraminal stenosis (2019 and 2024).

Figure 3. Analysis of the change in sagittal and coronal plane angles from the pre-operative pathological state to the post-operative state.



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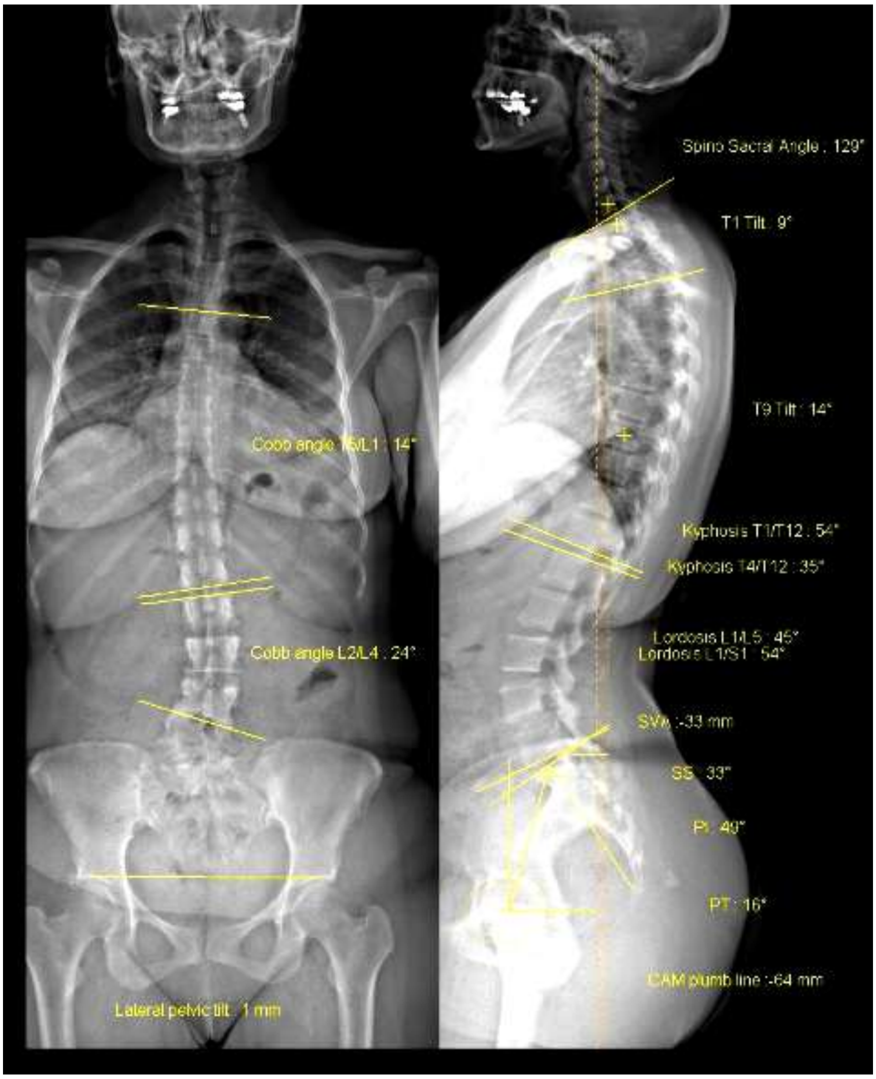

Figure 5. Intraoperative exposure post PSI_ALIF implantation.

Planning and Implant Production

Surgical Planning and Implant Design

Preoperative planning and implant design were conducted in collaboration with 3DMorphic Pty Ltd. (Matraville, Australia). Segmentation and three-dimensional (3D) reconstruction of the patient's CT scan were performed using Materialise MIMICs (Leuven, Belgium), enabling precise delineation of the hemivertebra, endplate morphology, and adjacent vascular structures. Haptic BioModels of the preoperative anatomy were then 3D printed in acrylonitrile butadiene styrene (ABS), providing tactile reference models for preoperative planning and intraoperative orientation.

Patient-specific implants (PSIs) were designed 3DMorphic Pty Ltd., (Sydney, Australia). The virtual surgical planning (VSP) process included detailed evaluation of vertebral morphology, vascular approach anatomy, vertebral alignment, and foraminal correction to optimise implant design and placement [10,13,14]. The superior and inferior implant surfaces were contoured to match the patient's endplate morphology, enabling intimate bone contact and optimised load transfer. Alignment correction was built into the implant geometry to address both coronal (scoliotic) and sagittal (lordotic) deformities. Virtual modelling allowed simulation of cage placement and foraminal opening, improving accuracy and minimising intraoperative guesswork.

A preoperative planning session was also held with a 3d model and cage model to assess ease iv implantation from the desired angle.

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Surgical Technique

The patient was positioned supine on a radiolucent table, and the L5/S1 level was confirmed with fluoroscopy prior to incision. A mini-Pfannenstiel incision was made, and a circular retractor system (Phantom, TeDan USA) was employed for a retroperitoneal approach. Mobilisation of the iliac vessels allowed safe exposure of the anterior L5/S1 vertebral body, performed by a vascular surgeon. The target level was reconfirmed with fluoroscopy.

A complete discectomy was performed, with meticulous endplate preparation using curettes and pituitary rongeurs to preserve the subchondral bone and optimise implant seating (**Figure 4**). Trial spacers were not required due to the patient-specific design; instead, intraoperative fluoroscopy confirmed the planned dimensions and trajectory. The selected PSI was packed with cancellous allograft bone and inserted under fluoroscopic guidance, with single-shot exposures used to verify position, alignment, and depth. Fascial and skin layers were closed in standard fashion. Skin-to-skin operative time was 3 hours, and estimated blood loss was 50 cc.

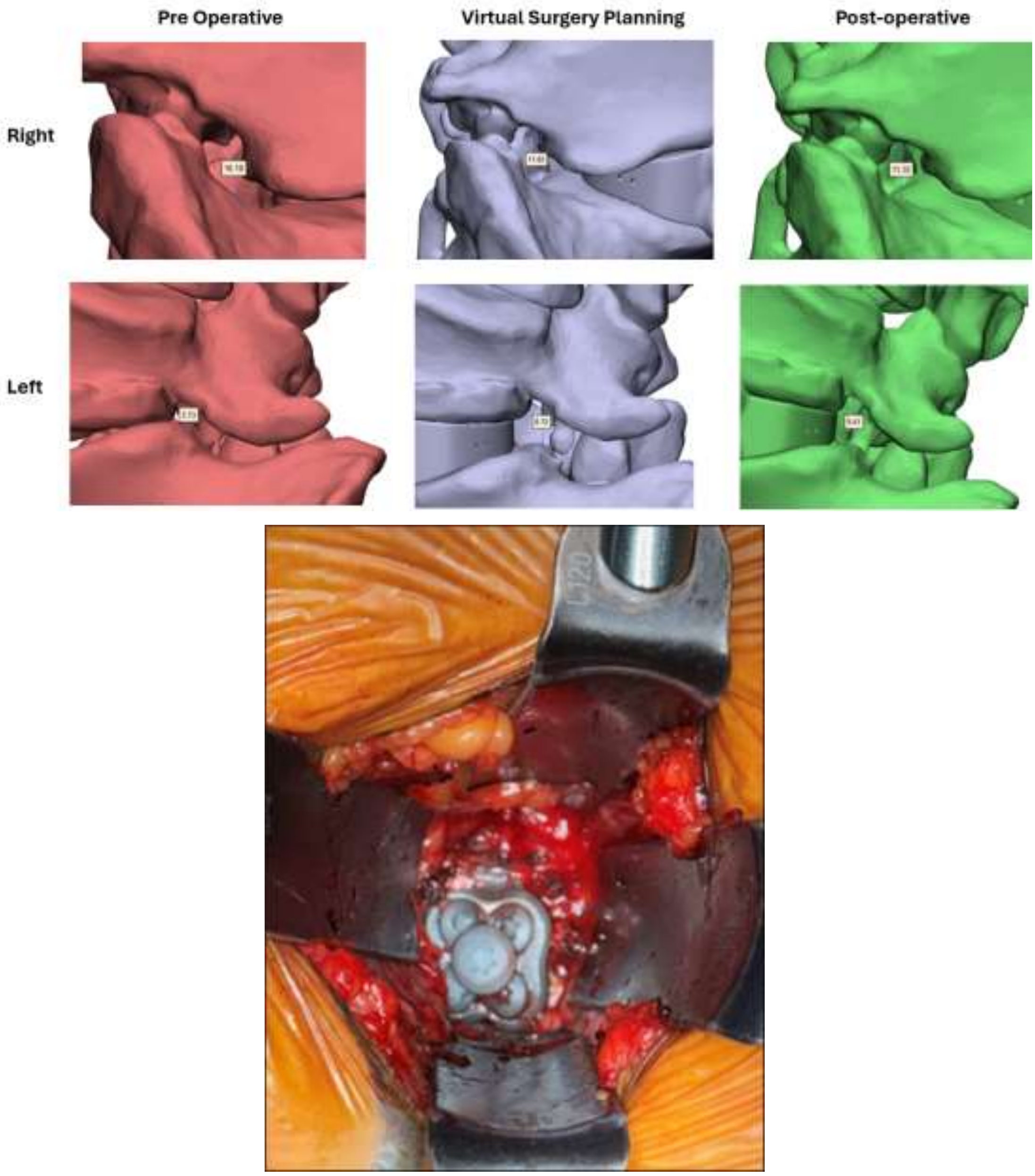

Figure 4. comparison of right and left L5-S1 foraminal aperture heights between the pre-operative pathological state, the planned correction and the achieved post-operative state.

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Throughout the procedure, the 3D-printed biomodel and virtual plan were referenced to confirm the orientation of the hemivertebra, foraminal stenosis correction, and the spatial relationship of vascular structures to the implant. Correct orientation was confirmed before implantation.

Implant Manufacturing

The PSI was produced using biomedical grade 5 titanium alloy (Ti6Al4V) (3DMorphic Pty Ltd., Matraville, NSW, Australia)[11]. Additive manufacturing allowed reproduction of the planned geometry with high fidelity. The overall implant architecture was designed to maximise endplate contact while permitting graft material packing through a large central window [10].

Conclusions

This case highlights the advantages of combining patient-specific implant (PSI) technology with virtual surgical planning (VSP) in the management of complex congenital spinal deformities. In situations where unique anatomical variations, such as hemivertebrae, present significant challenges to standard instrumentation, PSIs offer a tailored solution that conforms precisely to individual bony morphology, optimises implant fit, and facilitates accurate deformity correction. Decisions tailored to the patient's specific clinical problem (in this case, foraminal reconstruction) can be easily made.

Preoperative VSP enables a detailed understanding of regional anatomy—including vascular structures, endplate morphology, and deformity parameters—thereby enhancing surgical precision, minimising intraoperative uncertainty, and improving overall workflow. By planning screw trajectories, cage geometry, and approach corridors in advance, the surgical team can anticipate technical challenges and execute the procedure with confidence.

Importantly, this augmentative strategy offers a compelling alternative to traditional subtractive and potentially morbid approaches such as hemivertebra resection or complex osteotomies. By restoring alignment and decompressing neural elements through a customised anterior interbody reconstruction, major destabilising bone resections can be avoided, potentially reducing operative morbidity, preserving stability, and accelerating recovery. Together, PSIs and VSP represent a powerful and evolving adjunct to spinal deformity surgery, particularly in patients with complex or atypical anatomy, allowing for safer, more accurate, and less invasive surgical solutions.

Abbreviations

3DP	Three-dimensional printing
VSP	virtual surgical planning
PSI	patient-specific implants
ALIF	anterior lumbar interbody fusion
VACTERL	Vertebral, Anal, Cardiac, Tracheo-Esophageal, Renal, and Limb anomalies
ABS	acrylonitrile butadiene styrene

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