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# The Total En Bloc Spondylectomy Hybridization Surgery and its 3D-Printed Applications: A Review

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**ABSTRACT**
As the incidence of spinal tumors increases, so too does the demand for modern surgical solutions. Spinal tumors may begin as either metastatic or primary, but in both cases can develop rapidly causing a compression in the cauda equina nerve or spinal cord. Such compression causes neurological dysfunction, resulting in both tremendous pain and spinal instability. A key emerging surgical method in the removal of spinal tumors is the total en bloc spondylectomy (TES), a development of the previously popular en bloc spondylectomy. Since its development in 1989, the demanding and sophisticated surgical intervention has been gaining popularity and has now become accepted by musculoskeletal and tumor surgeons. The total en bloc spondylectomy serves as an effective approach in entirely removing the tissue which is damaged whilst not interfering with the spine's integrity. This procedure is done by various methods, all of which involve the careful reconstruction of the spine stability. In modern times, this surgery has been conducted in a hybridization format utilizing 3D-printers. This paper will delve into the four major 3D-printed components allowing for spinal reconstruction, artificial vertebral bodies, titanium cages, pedicle screws and rods, and guides. Similarities, differences, problems and more will be compared and contrasted whilst carefully examining the various printing methods, the biomaterials and each of their unique surgical applications.
**Keywords:** 3D-Printing, Spondylectomy, Spinal Tumor, Hybridization

## 1 INTRODUCTION

Distinguishing tumour tissue from healthy tissue during spinal surgery remains a major clinical challenge, increasing the risk of residual malignant cells and contamination of tumour cells to surrounding tissue, which may lead to an unsuccessful removal of the tumour [1]. A spondylectomy is a procedure used in medical practices to limit the recurrence of malignant tumours in the spine. However, it still carries significant limitations, as some of the malignant tissue cells may not be successfully removed by the end of the procedure. To limit the risks related to the spondylectomy, a new and improved version of the spondylectomy surgery is introduced. This is known as the total en bloc spondylectomy (TES), which removes the entire vertebrae, as opposed to only the malignant tissue [1]. TES is used for malignant tumours, aggressive benign tumours, as well as metastasis lesions [2].

This paper examines various types of biomaterials and manufacturing approaches used to create the TES implants, such as titanium alloys, stainless steel, biocompatible resins, carbon fibre reinforced polymers, hydrogels, and tantalum. It also reviews 3D printing methods, comparing the advantages and limitations of various biomaterials, illustrating their respective advantages, disadvantages, and limitations. Clinical implementations and a pediatric case study are presented, highlighting the use of the 3D printed implants in TES, as well as future developments that can be implemented. This paper aims to compare and contrast recent developments of 3D printing methods and applications, outlining the significance of the total en bloc spondylectomy (TES) 3D-printing hybridization surgery.

## 2 BIOMATERIALS

### 2.1 Titanium Alloys

Titanium alloys are materials mainly made of pure titanium combined with other metals or chemical elements. By mixing titanium with elements such as aluminium, vanadium, molybdenum, or niobium, the resulting alloy gains

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enhanced physical properties [3]. While pure titanium itself is strong—comparable to steel—its strength, durability, and flexibility are further increased when alloyed [3].
Titanium alloys are commonly used in various industries, including aerospace, medical, and dental fields. This is due to their unique characteristics which include a high strength-to-weight ratio, excellent corrosion resistance, and superior biocompatibility [4]. Despite these advantages, their machinability presents significant challenges due to their low thermal conductivity, high chemical reactivity, and strong work-hardening behaviour [4].

Titanium alloys are typically categorized into three main types: α, near α, and β alloys. Alpha alloys include stabilizers like aluminium or oxygen, contributing to their high-temperature stability [3]. Near-alpha alloys contain small amounts of beta-phase stabilizers, supplying a balance of strength and ductility. Beta alloys, with elements like vanadium or molybdenum, exhibit excellent strength, formability, and corrosion resistance [3]. Each is tailored for specific clinical needs. For example, β alloys are preferred for orthopedic implants due to their excellent flexibility, strength, and compatibility with bone tissue [3]. Applications of titanium alloys range from joint replacements (hips, knees) to dental implants and cardiovascular devices like stents and heart valves. The versatility of titanium alloys, paired with ongoing research into cost-effective production and alloying strategies, continues to expand their medical utility [3].

β alloys, which include elements such as niobium, molybdenum, and tantalum, are particularly significant due to their lower Young's modulus, which closely matches human bone, minimizing the stress shielding effect that can lead to bone loss [5]. These alloys also avoid using potentially toxic elements like aluminium and vanadium, which are present in traditional alloys. Instead, elements like zirconium and tin are used to enhance biocompatibility and mechanical properties [5]. The benefits of titanium alloys go beyond their strength. They have a natural resistance to corrosion due to a thin layer of oxide that forms on their surface, acting as a protective barrier [3]. This property, combined with their biocompatibility and lightweight nature, makes titanium alloys ideal for medical implants, such as joint replacements and dental prosthetics, where long-term performance and compatibility with human tissue are crucial.

Ti-6Al-4V, also known as Titanium Alloy Grade 5, is one of the most widely used titanium alloys due to its combination of strength, low density, corrosion resistance, and biocompatibility [3]. It is composed of approximately 90% titanium, 6% aluminium, and 4% vanadium, making it several times lighter than steel while maintaining nearly identical strength [3]. Ti-6Al-4V has a microporous structure, meaning it is composed of tiny pores [6]. These pores are loaded with antibiotics, nano-zinc oxide, anti-tumor drugs, and more [6]. This structure acts as a preventative to both tumor recurrence and infection. Furthermore, it has the ability to increase osseointegration between the implanted material and the biological host bone [6]. This alloy also has excellent resistance to oxidation and corrosion, even in harsh environments, and retains its mechanical properties at elevated temperatures of up to 400 °C [3]. Due to these advantageous properties, Ti-6Al-4V is extensively used across various industries. In the medical field, this alloy is a popular choice for orthopedic implants, dental implants, and surgical instruments, due to its biocompatibility and non-toxic nature [3]. Ti-6Al-4V is a high-performance material that is beneficial in industries requiring a combination of strength, durability, and corrosion resistance [3].

### 2.2 Medical Grade Stainless Steel

Stainless steel is a sturdy and widely used material mainly made from iron and carbon, with the addition of chromium to resist corrosion [7]. Unlike ordinary steel, which rusts due to its unstable, pure form of iron, stainless steel contains chromium that forms a protective layer of chromium oxide [7]. This layer shields the steel from air and moisture, preventing rust. Depending on the application, chromium is added in amounts ranging from 10.5% to 30%, resulting in over 100 different grades of stainless steel [7].

To achieve specific properties, additional elements like nickel, nitrogen, manganese, and silicon are added to stainless steel. Nickel can enhance flexibility, while nitrogen improves ductility [7]. Ensuring the correct alloy composition is very important, and technologies like X-Ray Fluorescence (XRF) and Optical Emission Spectroscopy (OES) are used for this purpose. Beyond its corrosion resistance, stainless steel is also valued for its ease of maintenance and aesthetic appeal.

Medical-grade stainless steel is a highly valuable material in the medical field due to its excellent mechanical strength, biocompatibility, and especially its corrosion resistance [8]. It is often used in making surgical implants, dental devices, and vascular stents. However, once inside the human body, stainless steel faces numerous challenges from complex physiological conditions, such as exposure to bodily fluids, varying pH levels, drugs, and microbial activity. These conditions can lead to different types of corrosion like pitting, crevice, and stress corrosion, which may affect the material's performance and safety [8]. This is why not all grades are suitable for medical applications. Medical stainless steel, commonly 304, 316, and especially 316L, is chosen for its specific composition, which includes approximately 60-70% iron, 16% chromium, 8-10% nickel, and small amounts of molybdenum and carbon to enhance corrosion resistance and durability [9]. These elements create a protective oxide layer that prevents rust and degradation when exposed to bodily fluids, cleaning agents, and even fluoride in dental care [10].

### 2.3 Biocompatible Resins

Biocompatible resins are specialized materials engineered to interact safely with living tissues and biological systems without causing adverse reactions [11]. Unlike a universal standard, biocompatibility is context-dependent, meaning a material's safety and effectiveness are evaluated based on its specific application and environment [12]. Typically, these resins are used in fields like healthcare, dentistry, and wearable technology, where they often come into direct contact with the human body. Before being approved for use, these materials undergo extensive testing and must comply with regulations like FDA standards, especially when applied to 3D printing. In the medical field, biocompatible resins contribute to the creation of artificial implants, artificial devices, stents, and surgical guides. Additionally, wearable devices such as fitness sensors, smartwatches, and medical wearables use biocompatible materials to ensure prolonged skin contact without causing irritation [11]. Sports equipment and fashion accessories also benefit from these materials, enhancing safety, comfort, and style. Ultimately, biocompatible resins play an important role in developing innovative products across different industries, prioritizing health, comfort, and user safety.

### 2.4 Carbon Fiber Reinforced Polymers

Carbon Fibre Reinforced Polymer (CFRP) is a blended material consisting of carbon fibres embedded within a polymer matrix [13]. This combination provides CFRP with strength, stiffness, and durability while maintaining a low weight. The polymer matrix plays a crucial role in binding the fibers, distributing loads, and protecting against mechanical and chemical damage [13]. In recent years, CFRPs have found noteworthy applications in medicine, particularly for orthopedic and dental implants. Their biocompatibility, radiolucency (transparency to X-rays), and mechanical properties similar to human bone make them an attractive alternative to traditional metal implants [13]. CFRPs also offer very good fatigue and wear resistance, reducing long-term degradation compared to metal implants. Additionally, they prevent issues associated with metal implants, such as interference with radiotherapy and imaging artifacts.

Despite their advantages, CFRP-based medical implants are not yet widely used due to factors such as manufacturing complexities and the need for extensive biocompatibility testing [13]. Manufacturing CFRPs for biomedical applications involves advanced techniques such as Carbon Fiber-Sheet Molding Compound (CF-SMC) and Fused Filament Fabrication (FFF), which enable high precision and customization for patient-specific implants [13].

### 2.5 Hydrogels

Hydrogels are three-dimensional (3D) networks of crosslinked polymer chains that can absorb and retain large amounts of water [14]. Their soft tissue-like structure makes them highly diverse across various fields. In the biomedical field, hydrogels are widely used for wound dressings, drug delivery, and tissue engineering, as they closely mimic the extracellular matrix, making them ideal for 3D cell cultures. Additionally, hydrogels provide a hydrated environment that protects encapsulated cells and biomolecules, promoting cell survival and tissue regeneration [15]. Their customized properties, such as density and swelling behaviour, influence solute diffusion and nutrient transport, which are critical for drug delivery and tissue engineering applications.

Hydrogels can be derived from natural, synthetic, or semi-synthetic polymers, and their properties can be modified for specific applications [14]. While some synthetic hydrogels may lack biodegradability, scientists are developing ways to enhance their environmental compatibility and biomedical suitability. Additionally, advancements in hydrogel formulations have led to injectable hydrogels that gel in situ, making them suitable for minimally invasive medical procedures [15]. However, challenges such as low mechanical strength and sterilization difficulties remain areas of active research.

## 3 PRINTING TECHNIQUES

3D printing modelling has become one of the most common manufacturing methods in the medical industry. 3D printing technology requires the use of modelling and designing the item required, along with ensuring that the correct type of printing is used, based on the material that is needed. Various methods of printing have been developed, in order to be compatible with the type of biomaterial that is being used for the implantation. The in depth analysis of various printing methods for the five different types of biomaterials discussed in this review are listed below. These materials are used in various surgical procedures. The focus of this review is the implementation of these printing methods in the total en bloc spondylectomy procedure.

### 3.1 Titanium Alloys

As mentioned above, titanium alloys are a universal biomaterial, due to their various physical and chemical properties, such as resistance to corrosion and minimal weight [16]. In order to successfully 3D print α, near α, and β titanium alloys, laser technology is used. This is because the printing process is very precise, as there are specific dimensions that need to be met in order to print. Some of the main printing methods for 3D printing titanium alloys are Selective Laser Melting SLM) and Selective Laser Sintering (SLS) [16]. Selective Laser Melting (SLM) and Selective Laser Sintering (SLS) both utilize a powder bed distribution system [17]. Utilizing this system, the 3D printed titanium implants can be easily customizable based on the requirements of the case and individual. The resulting titanium implants have a much higher application potential in comparison to other printing techniques for the alloy.

The process begins with the preparation of a fine polymer powder, which is evenly spread across the build platform. The powder is then preheated above the crystallization temperature to prevent deformation before a laser selectively melts or fuses specific areas according to the CAD model, forming the first layer [18]. The surrounding unprocessed powder remains loose, acting as a natural support and eliminating the need for additional structural elements. As soon as that layer is sintered, the build platform gradually lowers, and a fresh layer of powder is applied, repeating until the final structure is fully formed [18]. Controlled cooling is needed to maintain dimensional accuracy and mechanical stability. The main difference between SLS and SLM is the amount of power that is being inputted into the printing nozzle of the printer. SLM requires a higher laser power in comparison to SLS, as SLM produces the strongest 3D printed components. Although titanium alloys are one of the most widely used biomaterials in surgeries and implantations, 3D printing of these alloys is still limited. This is due to the fact that the material is costly and is difficult to process the raw materials in comparison to other biomaterials [1].

### 3.2 Stainless Steel

In order to 3D print stainless steel implants, the Selective Laser Melting (SLM) method is used [19]. As mentioned previously, this method uses a powder bed fusion process. In this process, the powder is added layer by layer. It starts off with a thin layer of metal powders in a building chamber, which then have a high power laser beam directed at them in the x and y direction, causing them to fuse together [19]. This process is then repeated layer by layer, which constructs the implant, until the complete implant that was required is constructed. There are many factors that affect the printing process of stainless steel. Some of these factors include scanning speed, laser power, and layer thickness [19]. SLM has a lot of advantages and is one of the main printing methods used in medical implants.

### 3.3 Biocompatible Resins

There are three main methods to 3D print biocompatible resins. The methods are as follows: Stereolithography (SLA), Digital Light Processing (DLP), and Material Jetting. Stereolithography utilizes UV lasers, which selectively cures the resin layer by layer [11]. By doing this, it is able to design and solidify the filament into the desired shape for the implant. SLA printing has extremely high resolution in comparison to other printing methods, resulting in it having a high resolution surface finish [11]. Similarly, Digital Light Processing (DLP), utilizes a light projector to cure the resin material layer by layer. This printing method is faster in comparison to SLA, as this method allows a complete layer to be printed, as opposed to a section of a layer being printed at a time.

### 3.4 Carbon Fiber Reinforced Polymer

Printing Carbon Fiber Reinforced Polymers is a growing area of research in the medical world. Currently, there is only one available printer that manufactures and prints carbon fibres composites continuously [20]. There are several factors that affect the performance of the implant post-printing. Some of these factors include the properties of the composite, the diameter of the printing nozzle, the thickness or other parameters of the composite, the environment that the implant is being printed in, and finally the post-processing procedure which includes the heat treatment and pressure to solidify the implant [20].

### 3.5 Hydrogels

Due to their biocompatibility and ability to mimic the extracellular matrix (ECM), a large network of proteins and molecules providing structural support to cells, hydrogels have become recognized as alternatives for 3D bioprinting. 3D printing techniques for hydrogels are diverse, including laser-based methods like Stereolithography, Extrusion-based printing, and Inkjet printing. An extension is 4D printing, where printed structures can evolve in response to stimuli, paving the way for innovations such as self-healing biomaterials and responsive tissue scaffolds. However, the most commonly used printing methods for hydrogels are the Inkjet printing and Extrusion-based printing.

Reactive Inkjet Printing (RIJ) is a 3D printing technique that creates solid structures through the precise deposition of ink droplets, which undergo immediate chemical reactions upon contact [21]. This method is particularly useful for producing hydrogel-based biomaterials, including those for tissue engineering. RIJ employs at least two printheads to dispense alternating inks that react upon deposition, forming solidified layers [21]. The process utilizes drop-on-demand inkjet technology, where a mechanical actuator generates a pressure pulse, ejecting ink droplets with high accuracy [21]. A crucial factor in RIJ is the rheological properties (properties of matter that deform and flow) of the inks, which must show low viscosity, appropriate surface tension, and high contact angles to ensure printability and structural stability [21]. RIJ has several advantages, including high resolution in the micron range, customization of construct dimensions, and the ability to print biomaterials with controlled porosity. Despite its potential, challenges such as optimizing layer thickness, preventing ink spreading, and improving mechanical strength must be addressed.

Extrusion-based printing requires a polymer or a viscoelastic polymer solution that is then pushed through a nozzle into the printing bed [22]. This then causes a flow of extruded material from the printing nozzle, which then cools down and solidifies into the implant. For viscoelastic materials, the printing nozzle is moved along the x and y directions, allowing for precise processing of the hydrogel [22]. The nozzles have a printhead diameter of 100µm to 1 mm, which allows for precise control of the printhead when designing and modelling the implant [22]. Furthermore, in this printing technique, the printing nozzle can be driven mechanically, with a screw to print viscoelastic material, or pneumatically, which uses compressed air as a method of extrusion [22]. To successfully 3D print hydrogels, the filaments, which are also known as the inks or melts of the printer, need to be viscous. The range for viscosity is as follows: 6 to 30 × 107 mPa*s [22]. There are various printing techniques, some more common than others, when it comes to 3D printing biomaterials. Based on the implant that needs to be created, and the material that is being used, specific printing techniques are used to successfully print what is needed.

### 3.6 Tantalum

There are many different ways to 3D print tantalum. The three main ways are using Laser Engineered Net Shaping (LENS), Electron Beam Melting (EBM), and Selective Laser Melting (SLM), which is explained above. LENS printing utilizes a laser system which melts material in order to deposit it layer by layer [23]. This printing technique does not require any molds in order to shape the implant to the desired shape. Rather, it employs techniques that have shorter production times, all while creating the implant needed [23]. EBM is a technique that uses high energy electron beams in order to liquify materials to combine the metallic materials, in this case tantalum. This printing technique has many benefits, such as having immense control when modelling the design, rapid formation of the implant, as well as high product strength [23].

## 4 APPLICATIONS

### 4.1 3D-Printed Artificial Vertebral Bodies

The first of the four applications is 3D-printed artificial vertebral bodies (AVBs). Such application is revolutionary in the field of spinal surgery, as the AVBs have the ability to simulate human anatomical normal function allowing for a complete match and a more compatible spinal reconstruction post resection [6]. This similarity in spinal curvature allows for a close fit to the lower and upper vertebral bodies resulting in a reduction in subsidence risk [6]. Lowering the subsidence risk is crucial, as it can cause physiological curvature, fractures such as nail-rods or adjacent vertebral, and more [6]. If the height of the subsidence increases beyond 5mm, there is a high chance of failure in reconstruction of the vertebral body [6]. A prevailing explanation for such occurrence claims it is a result of a difference in the elastic modulus of the implanted material and human bone [6]. Upon being tested, the AVBs had a far lower rate of subsidence when contrasted to conventional titanium mesh cages (TMC) [6].

AVBs have favourable structures and properties that allow them unique advantages. Such advantages include low modulus and high strength from the microporous structure, high adhesion of the bone tissue cells from the large contact area, and ability to promote maturation and differentiation of osteoblasts [6]. AVBs offer unique surgical advantages in not only precise anatomical matching, but in osseointegration [6]. Additionally, studies concluded that the 3D-printed artificial vertebral bodies were far superior when compared to TMC as the operation time, early complications, blood loss during the operation, and more were all reduced [6]. In traditional spinal surgery, operation time was prolonged as surgeons required time to determine which interbody fusion cage was most suitable. The determination process required repeated endeavours which ultimately led to high intraoperative blood loss [6]. Where spinal surgery with AVBs is different, is an MRI or CT of the full vertebral body is taken prior to the surgery, providing a complete model and detailed scan [6]. As a result, there is no need for the repetitive process of selecting the correct interbody fusion cage in surgery. This ultimately significantly lowers the operation time thus reducing intraoperative blood loss.

The artificial vertebral bodies are constructed of titanium alloy which is strong in biocompatibility, as mentioned above. The most commonly used titanium alloy is Ti-6Al-4V, an alpha-beta titanium alloy [6]. Ti-6Al-4V has incredible mechanical properties making it the perfect candidate for such an application as detailed above. In a case of a 12-year old body suffering from Ewing's sarcoma, a tumor that forms in particular bone or soft tissue types, a spondylectomy was required on the C2 vertebrae [24]. A titanium vertebral body was 3D printed for the spondylectomy and reconstruction [24]. It lowered the risk of dysphagia, difficulty with swallowing, and maximized its surface area contact between C1[24].

### 4.2 Patient Specific Drilling Guides

Another important application used in TES procedures is the patient-specific drilling guide (PSDG). Typically these guides are made of 3D printed biocompatible resins. These guides provide an alternative to stereotactic navigation by offering a customized, precise means of inserting pedicle screws in tumor surgery [25]. By improving accuracy and reducing operative time, PSDGs minimize the risk of complications such as screw misplacement and nerve damage. This technology also increases surgical precision, particularly in complex TES cases where anatomical landmarks may be distorted due to tumor involvement or prior surgical interventions [26]. The first step in printing the Patient Specific Drilling Guides is the modelling of the guide in the virtual surgical planning. An example of which can be seen below in Figure 1 for a case of a tibial plateau fracture.

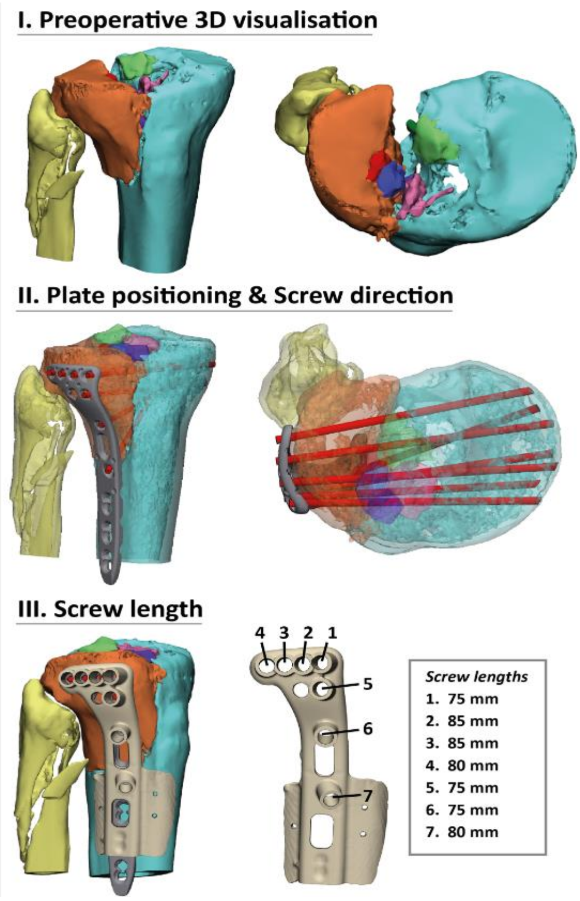


**Figure 1:** 3D-printed patient-specific drilling guide seen in virtual surgical planning [26]

In the case of a 28 year old woman who had been suffering from lower back pain since adolescence, a CT scan showed a bilateral L5 pars defect, and her L5 vertebra had to be reconstructed. A 3D model of the vertebra as well as a PSDG were printed and used to place a compression screw across the defect [27]. A combination of software and low-dose preoperative CT was done to find the necessary screw length, diameter, and best angle of trajectory. Pars repair using a posterior approach was performed with the guides positioned on the L5 lamina. The guides showed the trajectory for a 2.7 mm drill Kirschner wire and the tap and screw were implanted. A 5.00 mm cannulated compression screw with a washer was placed bilaterally along the defect and a bone graft was placed on the defect. By using a 3D printed PSDG, the screw sizes and trajectory were able to be determined pre-surgery, and the system's algorithm was able to detect the cortical breach, minimizing operational time and thus minimizing the rate of infection. The guide was also able to determine drill trajectory in an exposure that was smaller than usual. The cost of the PSDG operation is less than the cost of an operation that uses stereotactic navigation equipment.

### 4.3 Interbody Cage Implants

Interbody cage implants are critical in maintaining spinal integrity following TES operations. These cages are placed between two adjacent vertebrae after removing the intervertebral disc occupying the space [28]. Cages are typically used to treat Degenerative Disc Disease (DDD), spondylolisthesis, and spinal tumors or masses. The inside of the cage is hollow and filled with biomaterials that promote ossification, such as hydrogels. Various types of cages, including titanium mesh and expandable titanium, offer different advantages depending on the type of vertebral defect. For single-level vertebral defects, titanium mesh cages or expandable cages provide sufficient anterior column reconstruction [29]. Expandable titanium cages are associated with a low hardware failure rate and are beneficial for patients undergoing vertebral body resections to correct spinal deformities. However, both types of cages have limitations. Expandable cages produce an insufficient amount of bone graft and mechanical instability when used in extensive spinal column reconstruction, and mesh cages have a high rate of subsidence. Conventional reconstruction techniques often involve the use of an expandable cage with a vascularized graft. While effective, these methods pose risks such as cage migration, subsidence into adjacent vertebrae, and instrumentation failure. Long cages spanning multiple vertebral levels can cause further instability and increase the risk of late-stage complications. Studies have shown that 70% to 95% of cervical fusion [30] and 88% of lumbar fusion [31] can be attained by using interbody cages in spinal surgery, and using interbody cages is a factor to achieving solid bony fusion in the spine.

In a case reported of a 14-year-old girl with hemangioendothelioma, a rare form of cancer, a T9 vertebral body 3D printed cage implementation was successful [24]. The custom made implant maintained maximum contact with the endplate whilst catering to the kyphoscoliotic nature of her spine, her spine deviated from the normal spinal curvature [32]. 6 months later there was no evidence of integration and reportedly no complications [24]. Another patient had metastatic papillary thyroid carcinoma found to be in her C2-C4 vertebrae [24]. A custom 3D printed cage was used to model the remaining tissue supporting bones, osseous structures, allowing for points of attachment to the atlas and axis [24]. These attachment points are not possible with the standard titanium mesh cage.

### 4.4 Pedicle Screws and Rod Systems

In the posterior column of the spine, pedicle screws and rod systems are needed to provide durability. There are many different types of pedicle screws, sorted by locking mechanism, coating and augmentation, thread design, and materials. The screw and rod systems anchor screws into the pedicles of adjacent vertebrae and connect them with rods to maintain spinal alignment and support loads. These systems are typically made using titanium, particularly titanium-aluminium-vanadium or Ti-6Al-4V, due to its bioinert properties, lower modulus of elasticity resulting in a lower stiffness and reducing stress shielding, and resistance to corrosion. Titanium alloys also have a clearer magnetic resonance imaging (MRI) and computed tomography (CT) resolution [33]. Using titanium alloys particularly for pedicle screws improves screw pullout stability as well, being able to withstand large forces before being pulled out or having its head break [34]. Limitations of titanium alloys in these implants include fretting at screw-rod junctions which can lead to inflammatory reactions [35] and implant degradation, as well as galling from repeated friction, causing mechanical failure [36].

Another disadvantage of the rod and screw systems is rod fractures that can occur as a result of factors, such as location of resected tumor and history of radiotherapy. Studies have shown that TES at the lumbar level had the highest risk of instrumentation failure, followed by thoraco lumbar and thoracic levels [37]. Patients who did not undergo radiotherapy preoperatively or postoperatively did not experience rod fracture, whereas most patients who had a history of radiotherapy experienced rod fracture [37]. It is important to consider these factors, as rod fractures can be reflective of pseudoarthrosis in spinal reconstruction, and can lead to back pain and worsening neurologic function that require revision surgeries to correct.

**Table 1:** 3D printed applications used in TES surgeries.

| Applications | Anterior or Posterior Column | Materials | Advantages | Disadvantages |
|---|---|---|---|---|
| 3D Printed Prostheses | Anterior | • Titanium Alloys | • More compatible spinal reconstruction<br>• reduce subsidence | • Corrosion<br>• High cost |
| Patient Specific Drilling Guide (PSDG) | Both | • Biocompatible resins | • Low cost compared to stereotactic navigation<br>• Increase precision<br>• Reduced infection rates<br>• Reduced operation time | • Longer pre-operative planning<br>• Materials may degrade under sterilization conditions |
| Interbody Cage Implant | Anterior | • Titanium<br>• Carbon-reinforced polymers | • Low hardware failure rate | • Mesh has high subsidence rates<br>• Long cages increase rate of late stage complications<br>• Cage migration |
| Pedicle Screws and Rod Implants | Posterior | • Titanium alloys<br>• Stainless steel | • Pullout stability<br>• Clear CT and MRI imaging resolution | • Fretting leading to inflammatory reactions and implant degradation |

## 5 CASE STUDY

Hemangioma of the vertebrae are lesions highly vascularized, commonly found in adults [38]. The type can vary between capillary, cavernous or mixed, in all cases it is rare amongst the pediatric population [38]. Typically, vertebral hemangioma arises in the thoracic spine involving one vertebrae and potentially its surrounding elements or the vertebral body [38]. Although asymptomatic, it can result in spinal cord compression causing neurological deficits [38]. In spite of many surgical options, such as arterial embolization, vertebroplasty, tumor resection and more being available, total en bloc spondylectomy is being explored in pediatric patients [38]. In children, there is an up to 6% mortality rate due to blood loss, surgical options need to be reevaluated to provide specialized care for children [38]. A pediatric case of a total en bloc spondylectomy for a vertebral hemangioma was studied, a rarity. The patient of study was a fifteen year old boy presenting with gait instability, and frequent falls resulting from onsetting paraparesis [38]. Additionally, he had perineal paresthesia along with a two month history of paresthesia of the bilateral lower limb [38]. Spinal CT-scans, as well as X-rays revealed the T8 vertebral body honeycombing along with the MRI displaying an extensive T8 vertebral body tumor [38]. The patient underwent a 48 hour surgery with the aim of lowering intraoperative blood loss. After the success of the first surgery, the patient then endured the total en bloc spondylectomy on his affected vertebrae, T8. Subsequently, the pedicle screws were placed under fluoroscopy guidance along T4-T12 with the exclusion of T8 [38]. A temporary rod, right-sided, was implemented along the T4-T12 vertebrae [38]. Following this, both T8 pedicles underwent a partial resection [38]. A left-sided temporary rod was then placed along T4-T12 [38]. The temporary right rod was then removed, the right nerve root of the T8 vertebra was litigated and cut, and the T8-T9 transverse processes and rib heads were dissected [38]. A discectomy was subsequently executed on T7-T8 and T8-T9, resection of the posterior ligament running longitudinally was performed [38]. The T8 body was rotated completely then detached and taken out en bloc [38]. Replacing the T8 body, an intersomatic expansive cage was implemented with the help of a fluoroscopy [38]. Once satisfied with the spinal alignment, definitive bolts and spinal rods were placed with reinforcing lateral connectors [38]. Finally, thoracic drains on the left and right were left inside [38].

The total en bloc spondylectomy detailed above is being transformed as modern partnership with 3D printing has allowed crucial elements of the surgery to be customized to the patient on a case-by-case basis. The surgery varies relative to tumor location, patient history and more, 3D printing allows for this surgery to be customizable and the most beneficial for each patient's unique case.


**Figure 2:** "Preoperative imaging: CT scan (a, b) and MRI (c, d) showing extensive hemangioma of the T8 vertebra" (https://doi.org/10.1007/s00381-020-04954-3 ).

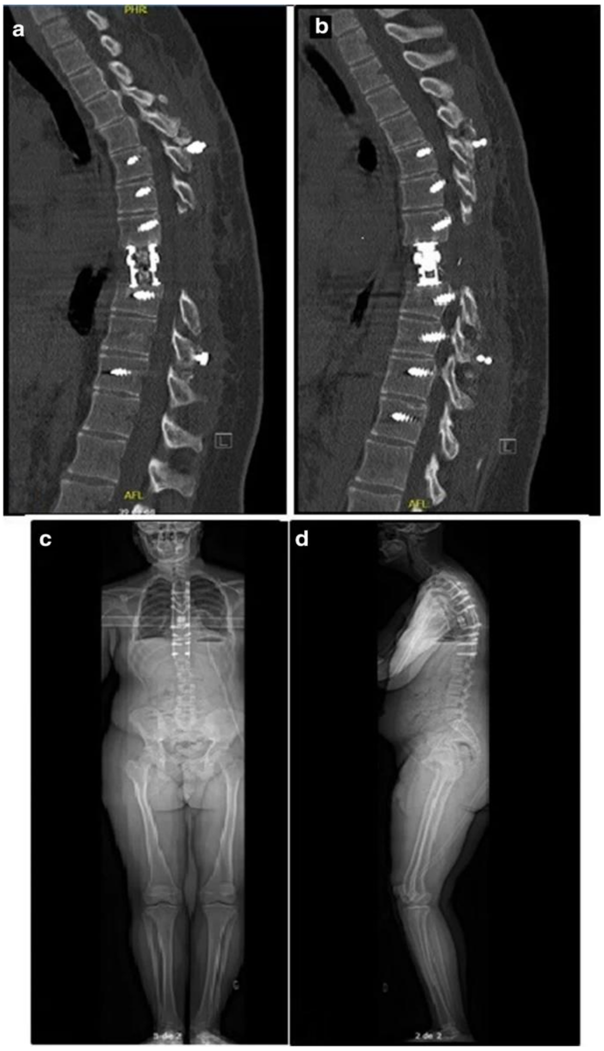


**Figure 3:** "Postoperative imaging: CT scan (a, b) and EOS X-ray (c, d) showing cage, bilateral screws, and alignment" [38].

### 6 FUTURE DEVELOPMENT

Whilst the TES operation has proven to be effective in its success rates, it is associated with various major risks. Some of which include injury of major vessels as the vertebral body is being dissected, instability of the spine from the spinal osteotomy, injury of the spinal cord, contamination to the surrounding body from the cells of the tumor, as well as bleeding excessively [1]. A range of methods and procedures are being studied to mitigate the risks and increase the rate of patient survival. When it comes to avoiding the risk of tumor cell contamination, multiple techniques have been developed and tested. The first, the T-saw, was designed to sharply cut the vertebral bone to reduce the chance of nerve root and spinal cord damage [1]. Its smooth surface inflicts minimal damage on the soft tissue surrounding the vertebral body. It has a minor diameter of 0.5mm and is composed of stainless steel wires which are twisted [1]. The T-saw has undergone many developments and is now able to provide easier cutting as it is constructed of diamond [1].

When residual tumor remains in the body post resection of the tumor, the tumor is guaranteed to regrow. In TES surgery, the surgeon ensures there is no residual tumor however there is a possibility of tumor cell contamination, which while low, has a chance of causing tumor regrowth [1]. Multiple cutting instruments were compared and tested to determine which has the lowest potential for tumor regrowth. The scalpel, T-saw, and Gigli saw performed incomparably when experimented on mice. The T-saw resulted in far less regrowth in tumor fragments it created in comparison to both the scalpel and Gigli saw [1]. Thus, as tumor recurrence was significantly lower with the T-saw, the T-saw is the safest tool for tumor cutting. Another method being used includes a unique chemotherapy method newly developed to eradicate cancer cells that were contaminated. It consists of exposing the tumor cells to distilled water for 2.5 minutes then to cisplatin, highly concentrated (0.5 mg/ml), for the same period of time [1]. Distiller water increases the osmosis of the tumor cells as well as the permeability of the cell's membrane to cisplatin entering the tumor cells cytoplasm [1]. This results in the contaminated tumor cells being eradicated [1].

In regards to instability of the spinal column, one idea being explored is the shortening of the spine [1]. The inserted vertebral prosthesis is slightly compressed by the adjusted posterior instrumentation [1]. This spinal shortening improves spinal cord function by causing an increase in spinal cord blood flow (SCBF) [1]. Additionally, the spinal stability of both the posterior and anterior columns are increased [1]. There are three potential phases for the shortening, phase 1, 2, and 3. The three phases are named the safe range, warning range, and dangerous range relatively [1]. The safe range shortens the spine within ⅓ of the vertebral segment [1]. There is no deformity or the spinal cord or the dural sac [1]. The warning range involves spinal shortening within ⅓ and ⅔ of the vertebral segment [1]. There is still no deformity of the spinal cord however there is buckling and shrinking of the dural sac [1]. Lastly, the dangerous range entails spinal shortening above ⅔ of the vertebral segment [1]. In this case, there is buckling dura and deformity of the spinal cord [1]. Spinal shortening in the safe range has been observed to cause an increase in SCBF, this is vital in spinal cord rehabilitation [1]. The shortening takes place in the concluding step of the TES reconstruction. Typically, the shortening ranges from 5-10mm, the safe range [1].

In terms of material future developments, whilst materials such as Ti-6Al-4V have proven to be superior in the surgical applications, many other materials are being explored to determine which has more applicable properties. One material includes porous tantalum, a material with higher success rates in regards to cell proliferation and adhesion [6]. Additionally, tantalum implants showed a compressive strength and elastic modulus that were controllable along with a significantly higher rate of new bone formation in comparison to Ti-6Al-4V [6]. As a result, although Ti-6Al-4V is currently the most commonly used material, research strongly suggests tantalum will become the material of focus for the future of AVBs. Tantalum is a hard and dense transition metal known for its corrosion resistance, biocompatibility, and high melting point [39]. These properties make tantalum a valuable material in various industries, particularly in medical applications such as implants and surgical instruments. Tantalum's ability to resist bodily fluids and its compatibility with human tissue make it ideal for orthopedic and spinal implants [6].

Tantalum is highly resistant to corrosion and does not react with bodily fluids, reducing the risk of reactions or implant rejection [6]. Unlike some other metals, tantalum does not trigger immune responses, making it ideal for long-term implants. It is widely used in hip and knee replacements due to its high mechanical strength and ability to integrate with bone tissue [6]. Another significant advantage of tantalum is its ability to increase bone formation. Its porous structure allows bone cells to grow into the implant, creating a strong bond between metal and bone [6]. Tantalum is often used as a coating on titanium implants to improve bone attachment.

Recent advancements in 3D printing have increased the use of tantalum in spinal implants, particularly in the development of artificial vertebral bodies for spinal reconstruction [6]. Compared to conventional titanium mesh cages, tantalum-based implants have several advantages. Tantalum has a lower elastic modulus than titanium, meaning it better matches the stiffness of natural bone [6]. This reduces the risk of stress shielding and implant weakening. Titanium mesh cages are prone to distortion, leading to implant failure in spinal surgeries [6]. Tantalum's load-bearing capacity and ability to integrate with bone tissue significantly reduce this risk [6]. The use of 3D-printed tantalum vertebral segments allows for customized implants tailored to a patient's specific spinal structure, to further improve the outcomes [6]. With continued advancements in 3D printing and material science, the role of tantalum in medical implants, especially spinal reconstruction, is expected to grow.

## 7 CONCLUSIONS

i. Total en bloc spondylectomy (TES) has become a vital surgical technique for managing spinal tumors, offering improved tumor control and reconstruction outcomes compared to traditional methods.
ii. 3D-printed technologies have significantly enhanced TES procedures by enabling patient-specific implants. This includes artificial vertebral bodies, cages, drilling guides, and fixation systems that improve surgical accuracy and reduce operative time.
iii. Biomaterials like titanium alloys, biocompatible resins, carbon-fiber polymers, hydrogels, and tantalum each provide unique advantages for spinal reconstruction, with emerging materials showing strong potential for superior osseointegration and mechanical performance.
iv. Despite these advancements, TES remains a high-risk, technically demanding procedure, with challenges including complications from instrumentation, risk of tumor contamination, and spinal instability, emphasizing the need for continued refinement.
v. Future innovations are expected to further increase the safety, precision, and long-term success of TES surgeries, especially when combined with customizable 3D-printed solutions.

## CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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