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Current applications of 3-dimensional printing in spine surgery

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ABSTRACT

Background: Three-dimensional printing (3D Printing) has emerged as a new technology in the early part of the 21st century, with promising applications in various industries, including the medical field. Spine care is a complex sub-specialty that has shown rapid inculcation of 3D printing. This technology is being used in pre-operative planning, patient education, and simulations, as well as intra-operatively for assistance in the form of patient specific jigs for pedicle screw placement and as implantable material in the form of vertebral body substitutes and patient-specific interbody cages.

Applications: 3DP in spine care has broadened the scope of minimally invasive and spine deformity surgeries. It has also enabled the production of patient-specific implants for complex spinal malignancies and infections. The technology has been embraced by various government organizations, including the US-FDA, which has drafted guidelines for the medical use of 3DP.

Drawbacks: Despite these promising advances and results, there still exist some significant drawbacks to the universal application of 3D printing technology. One of the main limitations is the dearth of long-term data describing the advantages and drawbacks in its clinical use. The widespread adoption of 3D models in small-scale healthcare setups is impeded by significant factors such as the high cost associated with their production, the requirement for specialized human resources, and specific instrumentation.

Conclusion: As technological understanding increases, newer applications and innovations in spine care are expected to unravel in the near future. With the expected surge in 3DP applications in spine care, it is imperative for all spine surgeons to possess a rudimentary understanding of this technology. Although there are still limitations to its universal use, 3DP in spine care has shown promising results and has the potential to revolutionize the field of spine surgery.

1. Introduction

The early part of the 21st century has brought with it the advent of three-dimensional printing (3D Printing) and its role in the medical industry. This technology has been used in various fields for the last three decades after its introduction by Charles Hull. Different terminologies such as Stereolithography (SLA), Rapid prototyping (RP) or additive manufacturing (AM) have been used to describe this technology in literature.[1] Currently, in the field of spine care, this technology is regarded as one of the most advanced tools to assist in the management of complex spinal conditions. Precision and duplicability are of prime importance to spine surgeons, and 3D printing helps to achieve these objectives. With continuous advancements in this technology, demand for its usage is expected to increase in the coming years, as is evident from the increasing traction it is receiving in the literature.[2] A survey of 282 spine surgeons from 57 countries found that there is a keen interest in incorporating 3D printing technology to improve accuracy and outcomes in spine care.[3]

This review aims to provide a concise overview of the clinical applications of 3D printing technology in spine care, along with a discussion on its limitations and challenges that hinder its widespread adoption.

1.1. Understanding the 3D printing technology

Three major methods of 3D printing are commonly employed for medical use: Fused deposition modeling (FDM), Selective laser sintering (SLS)/Electron beam melting (EBM), and Stereolithography (SLA).[1,4] Although FDM is a cost-effective method, it is unsuitable for intra-operative use due to the limited materials with a low melting point, making sterilization a challenge. On the other hand, SLS/EBM is a precise method capable of printing objects in the range of 0.5 mm, but it

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requires extensive post-printing processing to achieve a smooth surface. On the other hand, SLA produces the best quality materials but is relatively expensive.[5]

The common workflow of all 3D printing in spine care involves obtaining DICOM images from CT-scans/MRI of the patient to create a CAD model of the vertebral column. Thereafter, models of jigs and implants are created using a computer software (Fig. 1). One of the three aforementioned methods is then employed to print these models for per-operative use. These models are then printed for further use as deemed necessary (most commonly to understand the anatomy) (Figs. 2 and 3).

With the increasing use of these devices, it is crucial to establish and adhere to guidelines for the materials utilized during intra-operative procedures. Several organizations, including the FDA, have outlined guidelines for quality control during the production process for 3D implants.[6]

Despite the promising results of the technology, there are still limitations and challenges that need to be addressed. These include the lack of long-term outcomes supporting its clinical use, the prohibitive cost of 3D models, the specialized human resources required, and the need for specific instrumentation. These challenges hinder the widespread use of the technology, particularly in small-scale healthcare setups. However, with technological advancements and increasing understanding, newer applications and innovations in spine care are expected to unfold in the coming years. It is crucial for all spine surgeons to have a basic understanding of this technology, considering the expected surge in 3DP applications in spine care.

2. Applications in spine care

In recent years, 3D printing has been extensively used in spine care. Initially, it was primarily used to create biomodels to better understand and plan individual cases. However, over the past decade, 3D printing has been employed in almost all spinal pathologies. Its biggest contribution has been towards improving the accuracy of pedicle screw insertion techniques, which were prone to malpositioning.[7–10] Almost all of the spinal etiologies (infections, degenerative diseases, malignancies and deformities) have been managed using 3D printing at least partially.

2.1. Intra-operative instrumentation

Intra-operative instrumentation customized to each patient is now commonly used in the form of models created using 3D printing technology. 3D printing is most widely being utilized in this form even in 2nd tier cities and smaller hospitals. These are specific to a patient and are created either temporarily or permanently, as required. Patient images are shared with companies that provide the machinery for creating these models. 3D printing has been used across all spinal levels. This helps spine surgeons find solutions to complicated problems by providing patient specific and easy to use devices which would otherwise be impossible with the implants available with manufacturers.

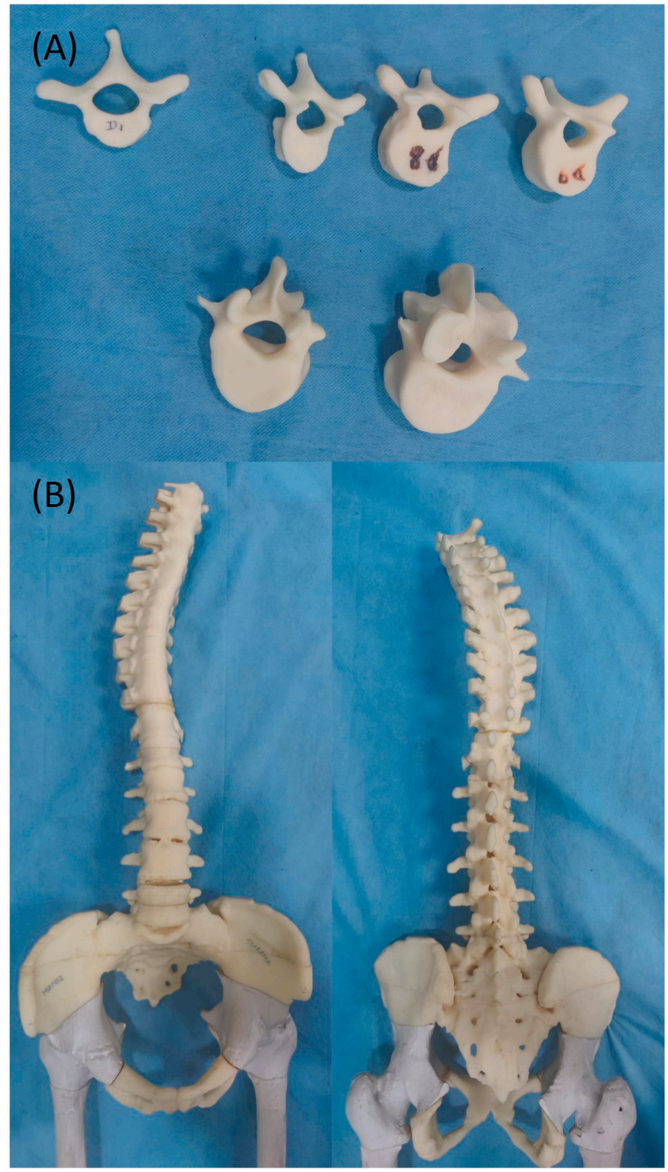

Fig. 2. Basic 3D models printed from the CAD file. A) Individual vertebrae. B) 3D printed combined vertebral column of a patient with a scoliotic deformity.

2.1.1. Pedicle screw guides (Figs. 4 and 5)

Pedicle screw malpositioning is a complication seen even amongst the most experienced spine surgeons. Pedicle screw guides, which are custom-made using 3D printing technology, have been found to be very effective in reducing complications such as screw malpositioning. These guides are specific to each patient and help in drilling the best path, thus decreasing operative time. Custom-made screw guides have been found to be effective in patients with degenerative scoliosis, upper cervical

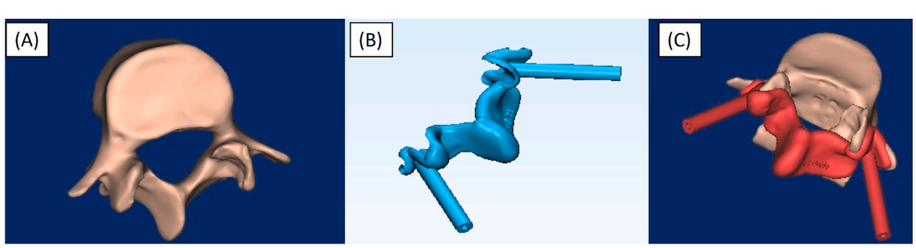

Fig. 1. A) 3D model of a vertebra created using the computer software. B) 3D model of the pedicle screw insertion guide created in the software. C) Representative mage showing the fitting of the pedicle screw guide over the vertebra in the 3D model.

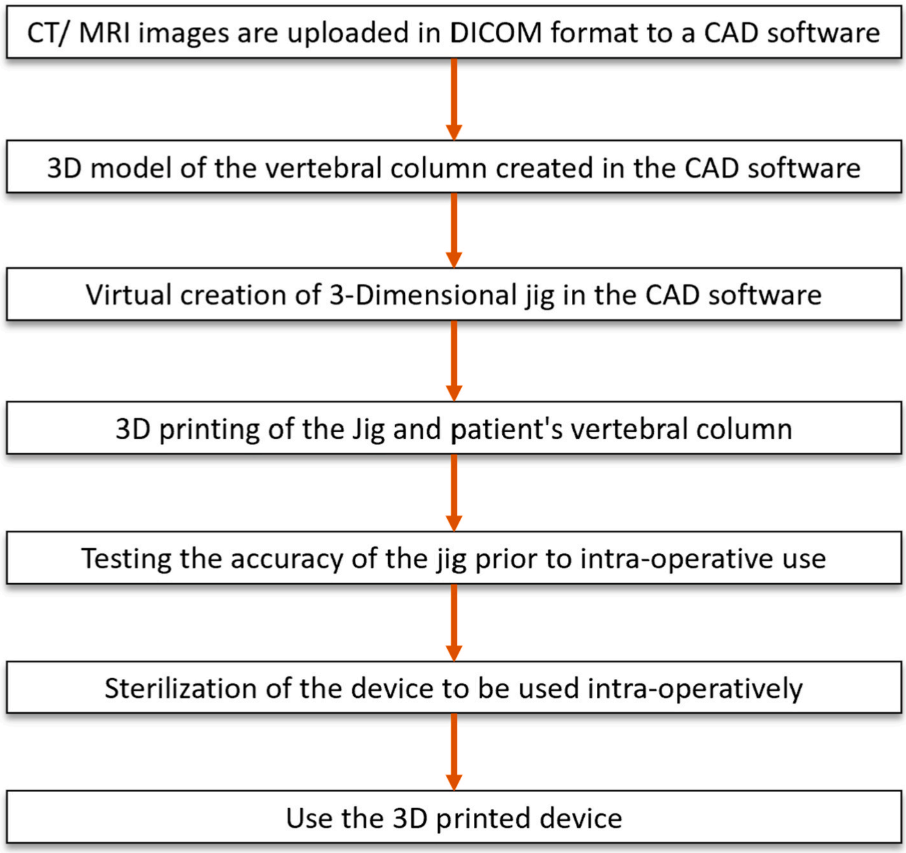

Fig. 3. Flowchart depicting the common workflow for employing 3D printed devices for intra-operative use.

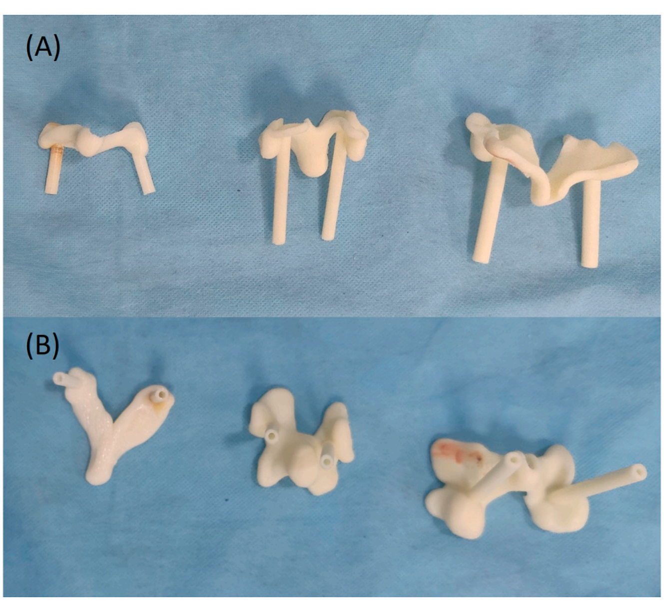

Fig. 4. A)Top view and B) End on view of pedicle screw guides created via 3D printing.

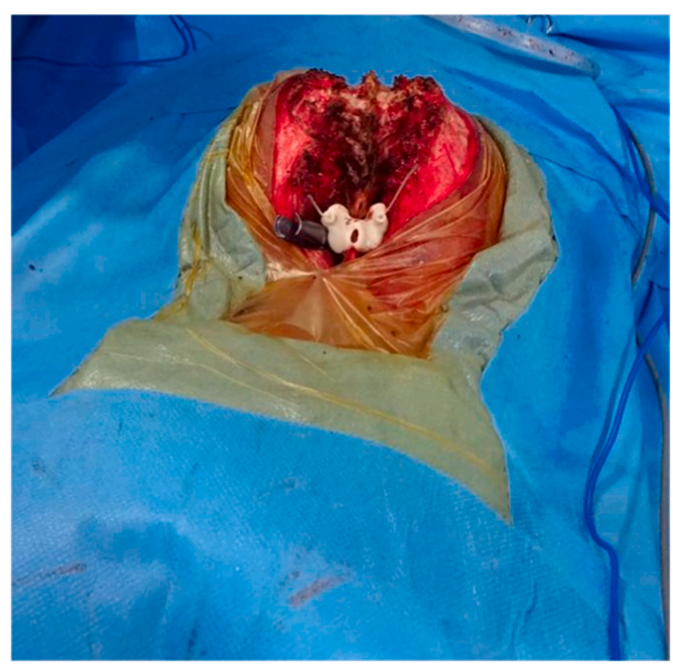

Fig. 5. Intraoperative image of pedicle screw guide in use for screw insertion in a patient with deformity.

fractures and in the narrow corridors for placement of compression screws.[7,8,11] Shi et al. have shown that cortical bone trajectory can be followed with more than 95% accuracy using custom made screw guides.[9] Supplementation techniques in the form of guides have also been shown to have increased accuracy in a larger study done by Mohar et al. in patients with thoracic scoliosis over 5 years.[10]

2.1.2. *Interbody cage and vertebral body substitutes*

Interbody cages have been created using 3D printing technology with features which enhance fusion and thus are drastically changing the outcomes of spinal fusion surgeries. These are drastically changing the outcomes of spinal fusion surgeries. These features decrease stress shielding while promoting integration which prevents complications ljke subsidence and pseudoarthrosis.[12] Polyetheretherketone (PEEK) is a commonly used high-performance thermoplastic in spinal implants. This material possesses high biocompatibility and when processed through "fused filament fabrication" (FFF) allows for improved osseointegration.[13]

Anterior column reconstruction is a challenging procedure especially in the cervical spine in patients who undergo resections for infections and malignancies. 3D printing has also been used to create custom-made vertebral body substitutes for the anterior column of the spine which has been documented in numerous case reports and cases series.[14,15]

2.2. Pre-operative planning

Pre-operative planning is of utmost importance when it comes to providing the best possible care to a patient It helps reduce errors and decreases the operative time. 3D printing has been shown to help simulate complex anatomies with the help of radiation-free biomodels especially in revision surgeries.[16] X-Ray compatible, coloured and transluscent models have also been described in literature. In a study by Parr et al. which talked about the benefits of 3D printing they have found that cost to health care providers can be reduced by reducing operative time with the use of biomodels.[16] Building up on these shorter operative times, Öztürk et al. showed that in trauma patients planned for posterior long-segment fixation 3D models help reduce blood loss and radiation exposure.[17] These models are also said to reduce the risk of surgery, as there is a better understanding of the relative positioning of structures. Galvez et al. probed into this benefit and noted that pre-operative planning using 3D models helped change surgical strategy which decreased the number and aggressiveness of surgeries.[18]

2.3. Deformity correction

Adolescent idiopathic scoliosis is commonly treated with bracing for slowly progressive curves which are $<50^\circ$. Custom bracing using 3D printing technology has been available since 2015, and while there are mixed results across the literature, the most significant benefit of using patient-specific braces is the ability to detect the pressures applied to the human body, leading to more comfortable treatment for the child without sacrificing the brace's effectiveness. Additionally, new braces with mesh-like materials have been developed, increasing patient comfort. Such orthoses have shown to improve mental health while not compromising on effectiveness.[19] 3D printed pedicle screw guides as mentioned previously have been employed with highest efficacy in deformity surgeries. They decrease operative time while minimizing malpositioning of screws even in the apex of the deformity thereby preventing iatrogenic injuries to vital structures. These can effectively form an alternative to the costlier intra-operative imaging systems that are now used in all centres where complex deformity corrections are undertaken.[20]

2.4. Patient and resident education

Patient education is crucial in improving patient satisfaction scores in the post-operative period, with illustrative models being shown to provide easier understanding of the surgery that they will undergo. 3D models can aid in resident training with the help of cost-efficient models that can provide tactile feedback and be stereographically sound. Custom-made models have been shown to have improved education even at the undergraduate level as opposed to radiographic images.[21] 3D models can be used as the situation demands and can help provide training in either minimally invasive or open procedures.[22] The ultimate test for 3D models was won when they outperformed saw bone models in a study by Burkhart. These models provide a haptically and biomechanically realistic simulation of posterior spinal procedures even in complex cases where saw bone models fail.[23]

2.5. Newer applications

In recent years, 3D printing has emerged as an innovative technology that has contributed to improving patient care and facilitating surgical procedures. The increasing accessibility of 3D printing has resulted in its widespread application in various research-related activities. Karimi et al. conducted a study that demonstrated the efficacy of using perpendicular forces in correcting scoliotic deformities, which was found to be more effective than using vertical forces alone.[24] Other innovations in surgical procedures have also been developed using 3D printing technology. For instance, a body surface percutaneous puncture plate has been described by Chen et al. which allows reducing the radiation exposure in patients undergoing percutaneous vertebroplasty. These have been shown to help optimize the surgery as well as decrease possible complications.[25] Additionally, patient specific positioning devices which improve comfort and decrease trauma to the skin during prone positioning for surgery and intra-operative patient specific retractors which improve visualization have been documented in literature by various researchers.[4] These newer advancements highlight the potential of 3D printing technology in improving surgical outcomes and patient care.

3. Drawbacks

Although 3D printing (3DP) technology holds great promise, there are several factors that have hindered its widespread use and acceptance in the realm of spine care. The absence of robust clinical studies unequivocally demonstrating its efficacy considering the significant cost and time investment has posed a major challenge. As such, the application of this technology in spine care is still relatively novel, and the use of 3DP in the field is still in its infancy. Several other concerns that impede its broad acceptance have been outlined below.

Cost: The costs associated with producing a single model have been a critical factor that has significantly hampered its potential use even in tertiary care centres. Both direct costs, such as software, material, and the hardware cost, and indirect costs associated with supporting trained individuals make it difficult for most health facilities to undertake in house 3D printing. Pijpker et al. have found that utilizing custom implants developed using this 3DP technology for occasional cases is not a feasible solution.[26] Therefore, a thorough discussion about the expense of treatment amongst all stakeholders is imperative.

Time: Planning and processing the computer-aided design model and printing the models and typically require at least one to two days, which has limited its use in emergency settings. Technological advancements are decreasing this time needed for development of models and also decreasing the post-processing time which may be needed to smoothen out the deficiencies of a printed model.[5]

Machinery: 3DP is a demanding and cumbersome technology that requires high performance workstations which includes specialized imaging devices, software and cost intensive 3D printers.[5]

Training: Trained personnel are required at each step to develop useable models. Collaborating between surgeons and engineers is necessary to understand the fundamentals and develop a model. Specialized knowledge of imaging devices is needed for determining the thickness of 2D scan slices. The CAD model software and 3D printing also need trained personnel who understand threshold values for segmentation, and can determine the best method of printing from the choices available.

Government approvals: As an emerging concept, definite rules and regulations detailing the use of 3DP are lacking in most countries. Currently, guidelines for its use are established in a few developed nations. Along with difficulty in obtaining approvals, the whole process is marred by legally complexities in the USA. China on the other hand has laid down technical considerations for artificial vertebrae and have regulations in place for registering 3D printed medical devices. India is lacking with respect to government support for these innovations as no clear guidelines are available which can lead to inadvertent complications if rules and guidelines are not established at the earliest.

Further advances in technology and studies detailing long-term outcomes of patients being managed with customized implants as opposed to 'off-the-shelf' implants will enhance the reach and acceptance of 3D printing in spine care.

4. Conclusion

The 3DP (3D Printing) technology has gained popularity among spine surgeons in recent times, and as our knowledge of the technology improves, it is expected to yield newer applications and innovations in spine care in the foreseeable future. With the expected surge in 3DP applications in spine care, it is imperative for all spine surgeons to possess a rudimentary understanding of this technology. Such printed implants, which are produced through 3DP technology, can streamline the surgical workflow, reduce the surgical time, and avoid intraoperative complications. Although there are still limitations to its universal use, 3DP in spine care has shown promising results and has the potential to revolutionize the field of spine surgery.

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Authors contribution

AK: Conceptualization; Data curation, Writing – original draft. BG: Conceptualization; Data curation, Writing – review & editing, Supervision; Validation.

Declaration of competing interest

None.

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