Chapter 1

3D Printing Biosphere for Medical and Orthopaedic Applications

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INTRODUCTION

3D printing is a form of the manufacturing process where an object is created in three dimensions in a layered fashion from a digital model. By keeping time slices of the cross-section on top of each other the creation is manufactured. 3D printing was originally called rapid prototyping and also goes by the name of additive manufacturing.

Medical rapid prototyping and 3D printing are ushering in a new revolution in healthcare by offering ingenious, innovative and personalized solutions to complex problems. Healthcare professionals are using the technology to fabricate intricate biosimilar models of the organs for surgical planning and simulation with clear advantages in terms of enhancing precision and improving the safety of surgical procedures. The 3D printing facilities also can rapidly manufacture patient-specific tools, personalized medical devices and patient-specific implants of various complexities and varied materials in an unprecedented short period. As the field of 3D printing continues to advance, there is no doubt that it will stand as a transformative force that promotes efficiency, ensures affordability and takes a patient-centric approach to create disruptions in every sphere of medicine.

TYPES OF 3D PRINTERS

As the sphere of technology expands, a variety of 3D printers customized for a specific job are being designed (**Fig. 1.1**). A few commonly used ones include:

- *FDM or fused deposition modeling printer:* The most common and the most expensive one available so much so that many households will have this printer. The process used by this printer is heating and extruding plastic filaments layer by layer which solidify to create an object.
- ***SLA or stereolithography:*** The SLA process uses a liquid resin that is cured (hardened) by a laser to create layers. It is known for its high level of detail and smooth finish.

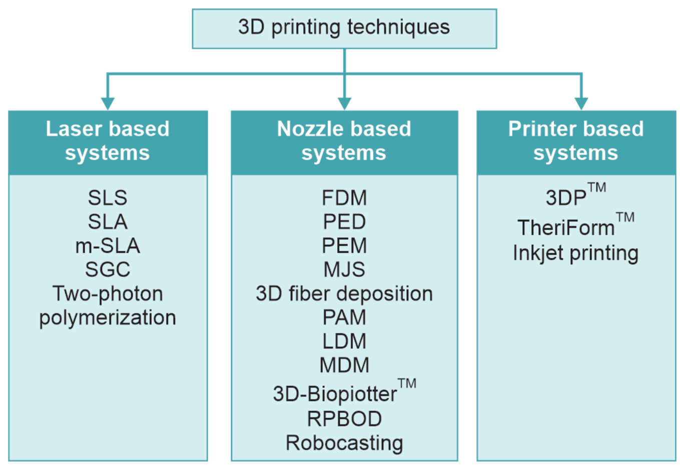

Fig. 1.1: Types of 3D printing technologies

- *SLS or selective laser sintering:* This process involves a laser to sinter powdered material usually polyamide or nylon, layer by layer creating strong yet flexible parts.
- *DLP or digital light processing:* Similar to SLA, DLP uses a light source, often a projector to cure liquid resin. It is faster than SLA because of its ability to cure the entire build in one go.
- *Binder jet:* By depositing the binding agent onto a powder bed an object is created layer by layer. The bound powder creates the object, and excess powder serves as support.
- *Polyjet:* The most versatile of all the printers. It works using the liquid photopolymers that get cured when the UV light is projected onto it. The printer can create multiuse and poly-colored prints simultaneously while maintaining the desired precision.
- *Material jetting:* The process is very similar to polyjet and the material jet deposits the droplet of materials in a layered fashion. The advantage is that several materials and colors can be incorporated into a single print.

Materials for 3D Printing

With so many different printer options, it is today possible to virtual print any material of choice that will be suitable for a diverse range of applications. They can be broadly categorized into:

- *Plastics:* These are by far the commonest used material for simpler 3D printing applications including school and home use. The three most commonly used plastics include:
  - *Polylactic acid (PLA):* This is easy to print and is the most basic inexpensive material.
  - *Acrylonitrile butadiene styrenes (ABS):* These are durable and relatively strong materials that are good choices for creating prototypes and even end-use applications.
  - *Polyethyelene terepthalate glycols (PETG):* These are transparent printing materials and combine the flexibility for strength. They make great use of teaching modules.
- Resins: These can be standard, flexible or tough quality.
- *Metals:* These attract maximum current manufacturing attention. The most commonly used materials include:
  - *Titanium:* It is known for its superior characteristics in a high strength-to-weight ratio making it ideal for medical and aerospace applications.
  - *Aluminum:* It is known for its lightweight and superior corrosion resistance properties. Because of this, it is one of the favorites of the aerospace industry.
  - *Stainless steel:* One of the earliest metals used for producing medical implants, the steel is strong and also corrosion resistant and thus amenable to diverse industrial and mechanical applications.
- *Ceramics:* The use of ceramics has increased over the last decade. These are primarily porcelain or clay-based. It is extensively used in the art sphere.
- *Composites:* These include carbon fiber reinforced filaments and metal matrix composites. The combination of two different materials with unique properties makes it a popular choice for the automotive industry.
- *Biocompatible matrices:* Although the widespread use of these materials is yet to be seen there is a great degree of hype around this material. This is in the hope that these bioinks and medical-grade resins will one day help us create compatible tissues and organ structures that can make these organs available off-shelf.
- *Others:* Several popular materials are used. Some of the other common materials include Wad, wood filaments and baking materials.

Orthopaedic application of 3D printing: The entire biosphere of 3D printing in orthopaedics can be classified broadly into four groups **(Fig. 1.2)**.

- 3D graphy
- 3D tools

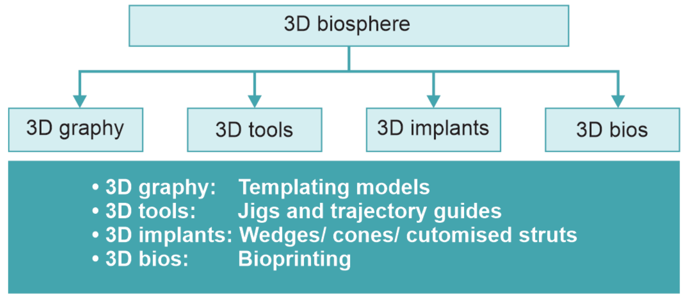

Fig. 1.2: Overview of 3D biosphere

- 3D implants
- 3D bios

3D graphy: This refers to creating models from the DIACOM image or CT scan of the patients. These 3D printed models can be used to understand the anatomy and injury pattern or pathology better. These can also be used to teach the junior doctors, residents and fellows. Some surgeons use it to explain the planned intervention to the patient or their caregivers. These models can also be used to simulate surgical steps. Many surgeons print even the normal un-affected side for certain cases and use them to template it in real-time during the surgery. The most common printer used for this purpose is FDM and the most commonly used material is ABS.

Steps of getting a 3D Graphy Model

- *CT scan:* Getting an appropriate CT scan is crucial to obtain the desired accurate 3D graph model. The Medical Rapid Prototyping Computer Tomography Protocol (MRCP) described by Bagaria et al is an attempt to offer standardization **(Table 1.1)**.
- *Thresholding and segmentation:* To process the area of interest a pixel's intensity must be compared to a predetermined threshold value. If the intensity is above the defined value, the pixel is classified as one of the groups of interest otherwise it is relegated to

TABLE 1.1: MRCP for CT scan image acquisition ideal for creating 3D printed bio-models

Parameters	*Description*
Field of view (FOV)	This is the region of interest. FOV measuring 12 × 12 inches is adequate
Scout	Depends on the region of interest and helps with planning
Region of interest (ROI)	ROI should be identified
kV	Automatic
mA	Usually automatic
Pitch	512 × 512
Collimation	1.25–1.50 mm
Slice thickness	1–1.5 mm
Slice increment	0.625–0.75 (less than 1 mm)
Kernel/algorithm	Moderate/soft tissue (not to use "bone/ detail")

another group. Segmentation is the next step and involves partitioning the DIACOM image into meaningful full areas of interest or printable objects. The hallmark of the process is that it goes beyond the normal binary categorization and aims to delineate and identify distinct identities like blood vessels or bone or solid organs. Together thresholding and segmentation are crucial for machines to interpret and understand the visual information.

- *Creating STL and G code:* STL file stands for stereolithography and is also called Standard Tessellation Language. This file format uses a collection of triangular facets to represent an object three-dimensionally. Each facet is supposed to represent a small flat triangle on the surface of a 3D object. This file format can be created using various 3D modeling software like Slicer, Osirix, Horros, Blender, TinkerCAD, or AutoCAD. In these programs, one can either design a 3D model or import a dicom image and export it in the STL file format, which represents the geometry of the object as a collection of triangular facets.

  G-code, on the other hand, is a language used in 3D printing to control the movements of the 3D printer. The G-code once generated tells the printer how to deposit material layer by layer to build the 3D object. The code contains instructions for the printer on how to move the print head, bed, and other components. G-code is generated using slicing software like Cura or Slic3r, which takes the designed STL file and converts it into a series of layers and corresponding G-code instructions.
- *Printing:* Fused deposition modeling (FDM) is one of the popular 3D printing technology that involves layer by layer additive manufacturing. To start the process, a spool of thermoplastic filament (commonly PLA or ABS) into the 3D printer. The filament is fed through a heated nozzle. Subsequently, the printer's nozzle is heated to the melting temperature of the filament. This ensures that the material is in a semi-liquid state for extrusion. The 3D printer begins printing the object layer by layer. The heated nozzle moves along the X, Y, and Z axes, depositing melted filament in the specified pattern outlined in the G-code. As each layer is deposited, it rapidly cools and solidifies. This process continues until the entire 3D object is built up. Support structures may be added for overhanging parts of the model. These are temporary structures that help prevent sagging or collapsing during printing. Once the printing is complete, the 3D printer may cool down, and the printed object can be removed. Some printers have automated bed levelling and filament detection features.
- *Post-processing:* This process involves removing any support structures, and performing additional post-processing such as sanding or painting. This could be a very elaborate exercise, especially if the intended use of the 3D printed object is beyond learning or understanding/ prototyping and the material is likely to be one of end use like 3D printed metal implants **(Figs 1.3 to 1.6)**.

3D tools: While various 3D printing technologies are available, the resin-based models printed using SLA or SLS technology are the most appropriate for creating these jigs. The process of making the jigs remains the same—obtaining the radiographic data, converting them into STL format and then superimposing a structure that is a mirror image of the particular patient's anatomy. While there is no standard design guideline available for the same, most engineers use proprietary software

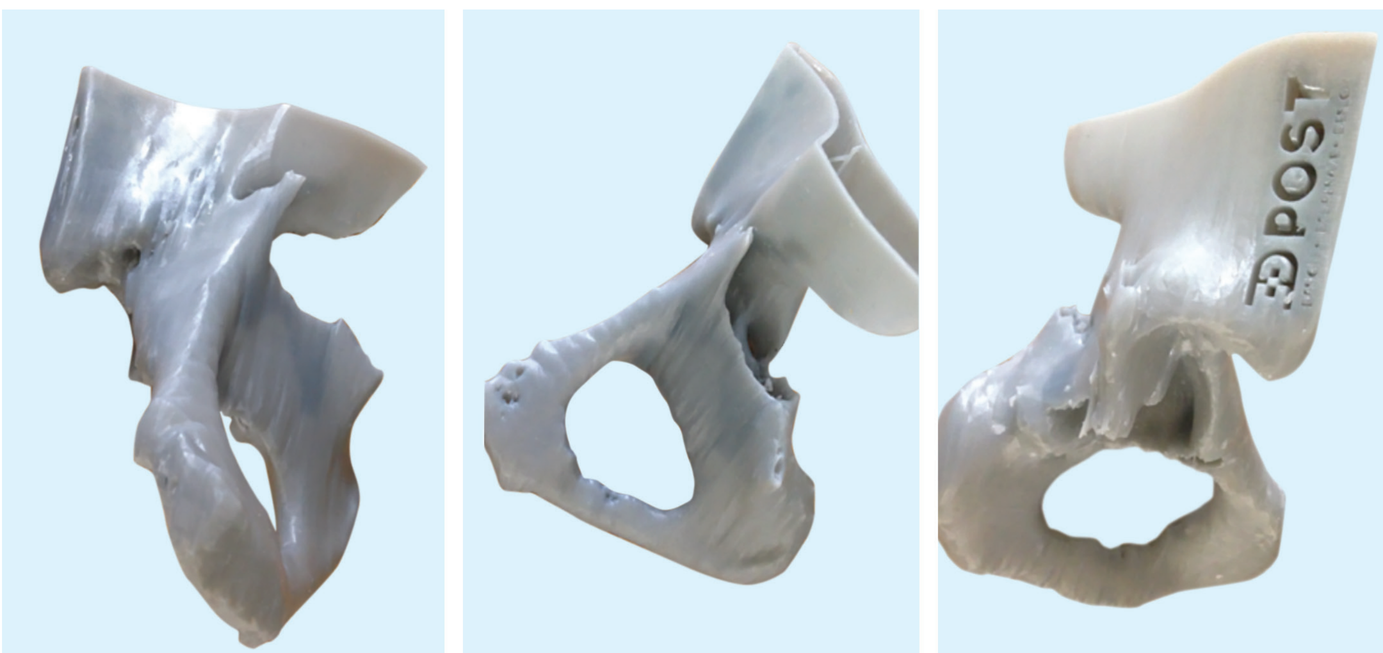

Fig. 1.3: 3D graphy models showing acetabular fractures

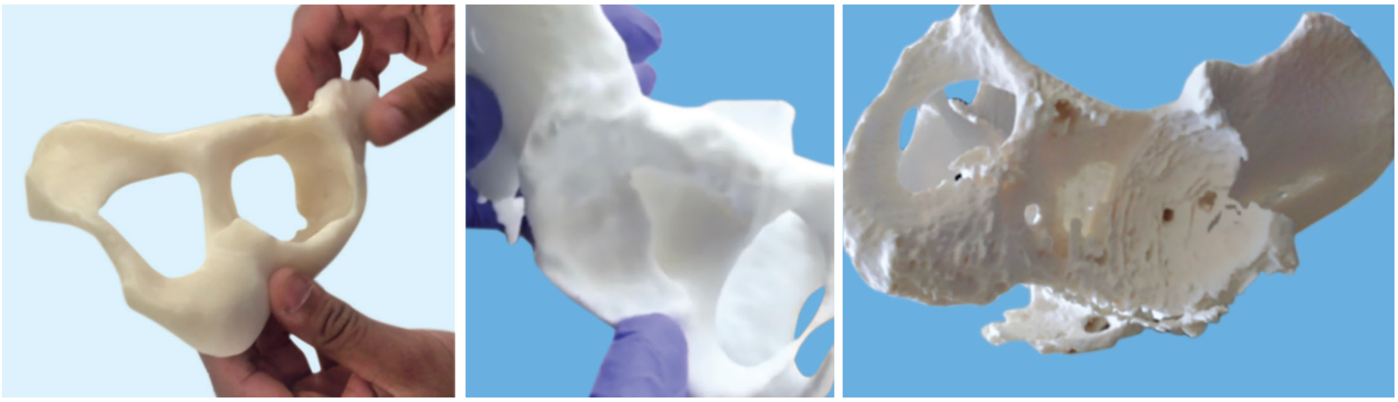

Fig. 1.4: 3D graphy model showing acetabular defects

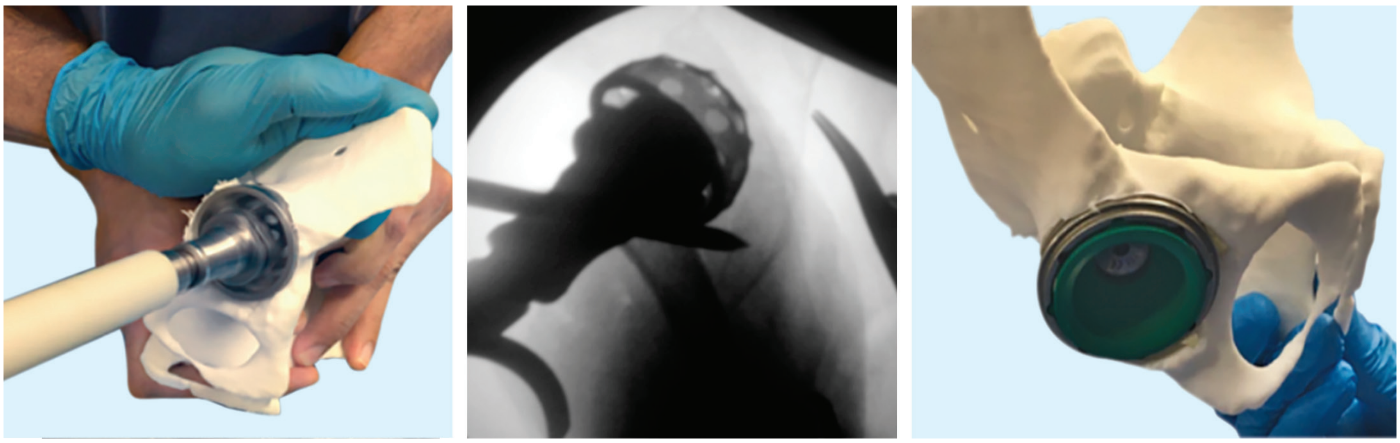

Fig. 1.5: Simulation on 3D graphy model

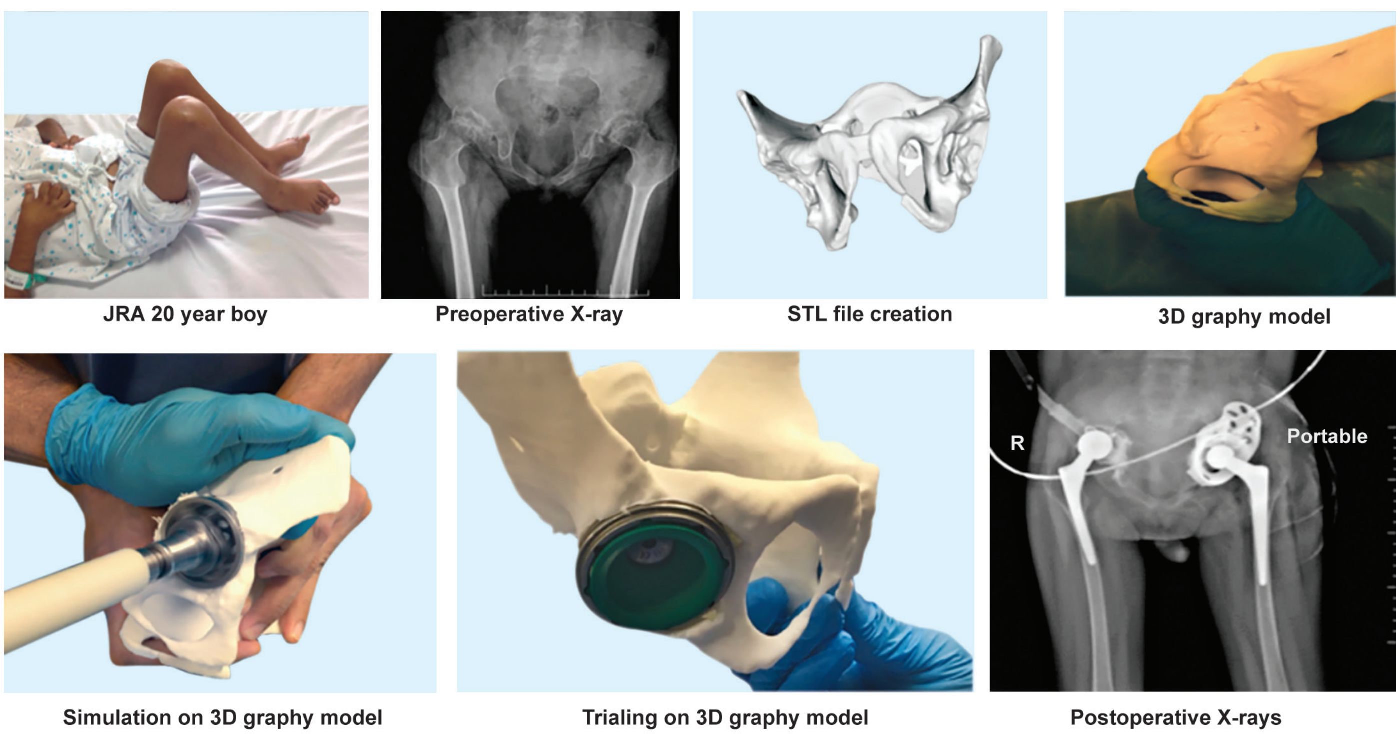

Fig. 1.6: Case summary showing the use of 3D graphy

like the one from materialize to make the workflow more intuitive. Most commonly they are used as patient-specific tools in TKR osteotomies, oncology resections and reconstructions and acetabular fractures

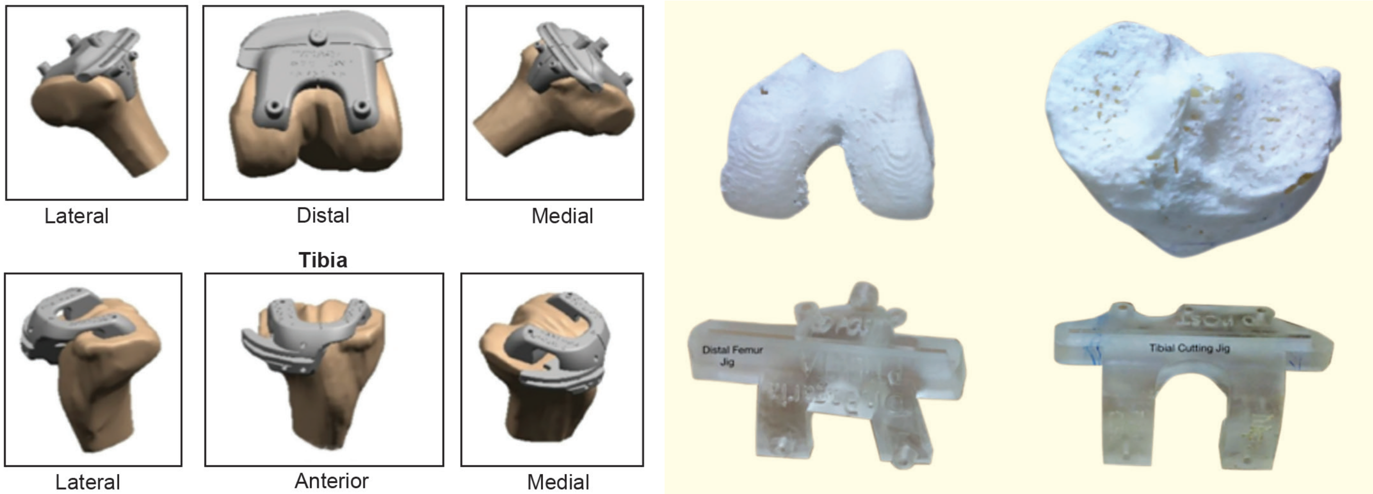

Fig. 1.7: 3D printed jigs for TKR

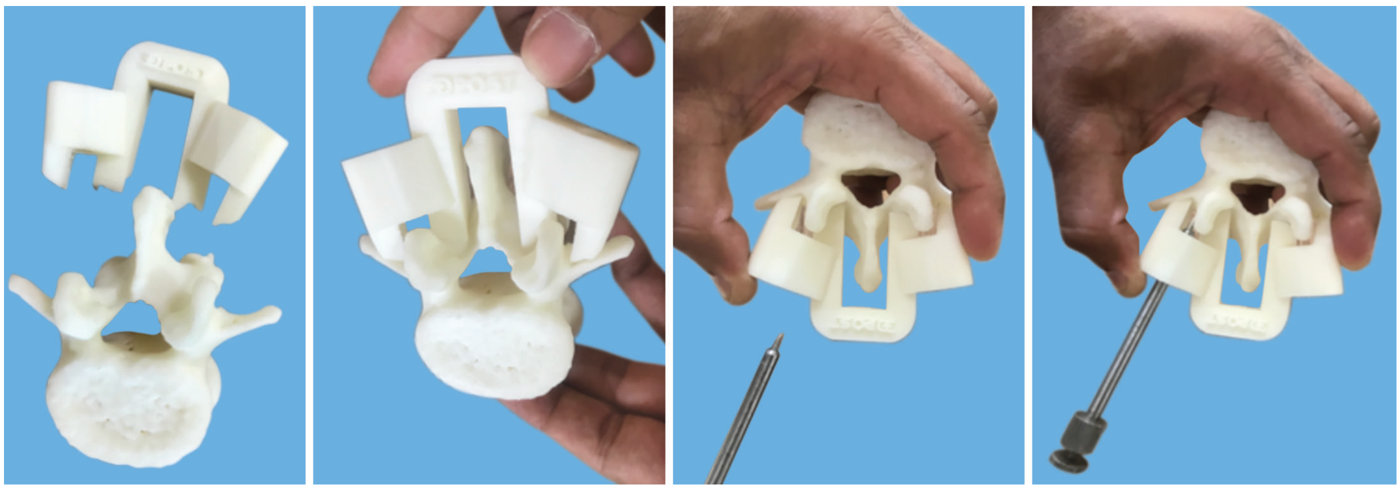

Fig. 1.8: 3D printed jigs for spine pedicle screw insertion

(Figs 1.7 and 1.8). Broadly the customised jigs can be classified as:

- Drilling guides
- Osteotomy jigs
- Implant positioning jigs

3D implants: With the use of 3D printing technologies, the fabrication of implants with intricate and complex geometries that would be challenging or impossible to achieve with traditional manufacturing methods can be rapidly created **(Fig. 1.9)**. One of the greatest advantages is that engineers can design implants with porous structures, mimicking the natural architecture of bone tissue. This porous design promotes better osseointegration, as it facilitates the ingrowth of surrounding bone, ultimately enhancing the stability and longevity of the implant. The flexibility in design afforded by 3D printing enables the incorporation of features like lattice structures, reducing implant weight without compromising strength and allowing strengthening of the implants differentially—reinforcing certain areas and lattice structuring the others much similar to Haversian and Volkmann's structures of the bone.

1990	• First 3D printed metal part using laser sintering
1993	• Patent filed for EBM process technology
1995	• SLM machine commercialized by EOS GmbH
2000	• EBM technology licensed by Arcam
2002	• First EBM machine launched by Arcam
2007	• CE certification obtained for 3D printed cups

Fig. 1.9: Timeline for manufacturing 3D printed implants

Today, the technology offers an unparalleled range of materials suitable for our applications, including medical-grade metals like conventional steel, titanium and cobalt-chrome alloys, as well as biocompatible polymers. These materials undergo precise melting or

TABLE 1.2: Comparison with EBM and SLM printers

Features	*EBM*	*SLM*
Head source	60 kW electron beam	Laser beam
Scan speed	Magnetic driven; fast	Limited secondary to galvanometer inertia
Powder size	45–105 microns	10–45 microns
Minimum beam	140 mm	50 mm
Pool dimension	2–3 microns	0.5–1.5 microns
Layer width	50–200 microns	20–100 microns
Chamber milieu	Helium (vacuum)	Nitrogen or argon
Temperature	400–1000°C	100–200°C
Residual stresses	No	Yes
Surface finish	Moderate to poor	Excellent

sintering processes during 3D printing, resulting in implants with optimal mechanical properties. The ability to select the appropriate biocompatible materials based on the specific requirements of each case and variety of implants contributes to improved outcomes and reduces the risk of adverse reactions.

Selective laser melting (SLM) and electron beam melting (EBM) as compared in **Table 1.2** are commonly used for metal implants, allowing for the layer-by-layer fusion of powdered metals. These techniques offer high precision and resolution, enabling the creation of intricate structures. Additive manufacturing also minimizes material wastage, making the process more sustainable compared to traditional subtractive methods.

3D bios: Bioprinting or the ability to print live human tissues—considered the final frontier for modern medicine is gradually but steadily emerging as a potentially transformative force using 3D printed technologies. The technology involves layer by layer depositing the live cells along with the biomaterials and supporting structures to create the biological construct that three-dimensional MIMICS live structures. The ability to accurately position cells and biomaterials in the pre-decided and predesignated pattern is promising for regenerating damaged tissues, especially the bone, cartilage, skin and even organs like the liver or heart. In all these processes, the ability to select the suitable bioink is crucial as these bioinks must provide a conducive environment for cell growth, support the development of the functional tissues and maintain structural integrity throughout the entire process **(Table 1.3 and Fig. 1.10)**. One of the most commonly used bioinks is the one made up of hydrogels—which are either natural or synthetic polymers mimicking natural matrices.

As the promise and potential of bioprinting are immense, they also bring about immense challenges and ethical considerations in play. Technically, ensuring the functionality, safety and long-term viability of bioprinted tissue remains a formidable task. Ethical concerns

TABLE 1.3: Commercially available 3D printed implants

Manufacturer	*Brand of the cup (TM)*	*Porosity*	*Properties*
Zimmer	G7	OsseoTi	475 microns, 70%
Smith nephew	Redapt	Coneloc porous Ti	202–934 microns, 67%
Stryker	Trident II	Ti AMagine	100–700 microns, 70%
Adler	Agilis Ti-Por	Ti-Por	700 micron, 65%
Corin	Trinity plus	Porous layer unique structure (PLUS)	300–900 microns, 50–90%
Materialise	aMace	aMace	720 microns, 70%
Medacta	Mpact	3D metal	600–800 microns, 60–80%

Fig. 1.10: 3D printed cup

related to the creation of 'living' matter too need to be deeply thought out and executed well. As is with so many powerful technologies, striking the right balance between innovation and ethical responsibility is crucial for responsible advancement.

The future of 3D printing: 3D printing is well poised to revolutionize all aspects of patient care in Orthopaedics and traumatology. Its diverse application right from advanced imaging, patient-specific implants and tissue printing is set to usher in a new era of precise, optimized, personalized, patient-specific care in Orthopaedics. The revolution will be orchestrated by evolving relationships amongst the key players—Orthopaedic surgeons, engineers and researchers who will be instrumental in shaping this transformative journey. This future landscape is also likely to be heavily influenced by the integration of data analytics and artificial intelligence. Machine learning (ML) algorithms that can analyze huge swathes of data related to patient outcomes, implant design and surgical technique will be used to optimize Orthopaedic care. This data-driven approach will refine implant designs, predict patient-specific responses and enhance support for improvement in care.

As the technology continues to grow and become widespread and accessible, the key to future growth is the promise of increased global availability and cost efficiency. Localizing bureaus that support 3D printing technologies in cost-efficient manners will reduce the need for extensive transportation and nurture local talent. This important step in the democratization of technology is key to ensuring that technology to make advanced Orthopaedic solutions is available to all patients across the globe.

BIBLIOGRAPHY

1. V Bagaria, R Bhansali, P Pawar. 3D printing-creating a blueprint for the future of Orthopaedics: current concept review and the road ahead! Journal of clinical orthopaedics and trauma. 9(3):207-212.
2. Senkoylu A, Daldal I, Cetinkaya M. 3D printing and spine surgery. J OrthopSurg (Hong Kong). 2020 Jan-Apr;28(2): 2309499020927081.
3. V Bagaria, K Chaudhary. A paradigm shift in surgical planning and simulation using 3D graphy: experience of first 50 surgeries done using 3D-printed models. Injury, 48(11):2501–2508.
4. Feng Y, Zhu S, Mei D, Li J, Zhang J, Yang S, Guan S. Application of 3D Printing Technology in Bone Tissue Engineering: A Review. Curr Drug Deliv. 2021;18(7):847–61.
5. Ran Q, Yang W, Hu Y, Shen X, Yu Y, Xiang Y, Cai K. Osteogenesis of 3D printed porous Ti6Al4V implants with different pore sizes. J Mech Behav Biomed Mater. 2018 Aug;84:1–11. doi:10.1016.
6. Garg B, Gupta M, Singh M, Kalyanasundaram D. Outcome and safety analysis of 3D-printed patient-specific pedicle screw jigs for complex spinal deformities: a comparative study. Spine J. 2019 Jan;19(1):56–64. doi: 10.1016/j.spinee.2018.05.001.
7. V Bagaria, A Sharma, O Sadigale. Predicting the Future of Orthopaedic Trauma Implantology. Handbook of Orthopaedic Trauma Implantology. 123–142.
8. Trace AP, Ortiz D, Deal A, Retrouvey M, Elzie C, Goodmurphy C, Morey J, Hawkins CM. Radiology's Emerging Role in 3D Printing Applications in Health Care. J Am Coll Radiol. 2016 Jul;13(7):856–62.e4.
9. D Shah, L Naik, B Paunipagar, D Rasalkar, K Chaudhary, V Bagaria. Setting up 3D printing services for orthopaedic applications: a step by step guide and an overview of 3D biosphere. Indian Journal of Orthopaedics. 54, 217–227.
10. Aimar A, Palermo A, Innocenti B. The Role of 3D Printing in Medical Applications: A State of the Art. J Healthc Eng. 2019 Mar 21;2019:5340616. doi: 10.1155/2019/5340616. eCollection 2019.
11. V Bagaria, S Deshpande, DD Rasalkar, A Kuthe, BK Paunipagar. Use of rapid prototyping and three-dimensional reconstruction modeling in the management of complex fractures. European Journal of Radiology. 80(3):814–820.
12. V Bagaria, A Kuthe, S Deshpande. Use of rapid prototyping and three-dimensional reconstruction modeling in management of complex acetabular fracture. Current Orthopaedic Practice. 20(3):337–340.