

CHAPTER 16

Neurosurgical Techniques and Training in Three-Dimensional Models

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Introduction

The use of three-dimensional (3D) printing models in neurosurgery has become increasingly widespread in recent years for surgical training, pre-surgical planning and specialist training. In spinal surgery, which is anatomically variable and a challenging area in practice, it is important that surgeons adapt to the anatomy of the individual patient.

Both the training and learning of complex surgical procedures applied in the specialty of Brain Surgery training is quite difficult. Many studies have supported that this challenging training process is completed more effectively with the use of three-dimensional models, and these models are gaining importance in brain surgery training tools (Bohl et al., 2019).

One of the major disciplines of medicine is anatomy. Classically, surgical neuroanatomy is often learned from 2-dimensional images in books or from cadavers that can rarely be obtained. Digital presentations, video recordings and two-dimensional visual methods are still used today for the anatomy training of medical students and surgeon assistants. (Kurt et al., 2013). Three-dimensional training of branches with spatial characteristics such as anatomy will lead to much more successful results. Cadavers continue to be the gold standard for applied neuroanatomy training today, they are at a disadvantage compared to 3D models in terms of storage difficulty and cost. In addition, it is not possible to provide cadavers and storage facilities in every medical training center. Among its disadvantages is long-term exposure to formalin solutions used to protect the cadavers, which are harmful to health. (Hauptmann et al., 2009).

3D prints of anatomical structures produce physical models for pre-operative planning and applied training. Also, surgical intervention can be simulated with these models. Realistic simulations that allow the surgeon to try the operation at the desired frequency reduce the incidence of patients exposed to complications that may arise during surgery (Anderson et al., 2016) (Mashiko et al., 2015). 3D printing technology, which can also be used for the manufacture of surgical devices, can produce instruments and implants suitable for the patient's own anatomy (Chang et al., 2014). Thanks to

technologies such as intraoperative navigation and 3D modeling, better clinical outcomes and reduced rates of complications in spinal surgery have been.

3D implants are specific to the patient and one of their advantages over traditional implants is the possibility of printing the porous structure of the trabecular bone. Thus, better anatomical matches and fusion are possible due to the inclusion of the biological components in the bone structure as well as the patient's suitability with its own anatomy in terms of shape and size. (Liebsch et al., 2020). If effective and routine clinical use of 3D printing methods is ensured, this will revolutionize the treatment of many spinal diseases.

History and Development Stages

The three-dimensional printer technology was first introduced in 1981 by Dr Hideo Kodama to produce a device using ultraviolet rays (Attarilar et al., 2021). The technology then developed by Charles Hull led to the production of the first three-dimensional printer in 1983. There has been a continuous development since then until now. The modeling information of printers capable of producing models in almost every structure and geometry is obtained from routine pre-operative imaging (magnetic resonance imaging, computed tomography, etc.) (Azlin et al., 2022).

The first use of 3D models in spinal surgery was in 1999 as a method to assist with imaging in patients with severe spinal deformity (D'Urso et al., 1999). In these studies, D'Urso and ark. used 3D anatomical models in the treatment of spinal deformities, occipital and maxillary lesions caused by osteogenesis imperfecta (Yang et al., 2015).

The increasing prevalence of affordable 3D printing software and hardware has promoted the adoption and exploration of clinical use as a technology. Clinical 3D printing units have been established in the United States as a subsidiary of clinical departments. The establishment of these units aims at the mass production of 3D models to be used in surgical planning, instruction or assistant training. In these units, it allows clinicians from different fields of expertise to take advantage of manufacturing services to obtain 3D models.

3D printing technology has contributed to many medical fields including the pharmaceutical industry, plastic surgery, brain surgery, and orthopedics (Fan et al., 2020) (D'Urso et al, 1999). 3D technology is a field that has proven importance in the production of anatomical prostheses, surgical practice, training and planning, production of tissue and organ models. (Mukherjee et al., 2017). 3D printing techniques have evolved over time and reached standards that can be used in medical applications. Orthopedics, plastic surgery, spinal surgery have been the first branches to use these techniques in the clinic.

Technologies

3-Dimensional printing techniques are techniques in which various manipulations are performed to create 3-dimensional objects. Additional or extractive methods have been used in printing. Extractive method is known as Computer Numerical Controlled (CNC). The biggest disadvantage of this method used to create 3-dimensional models is that it requires a variety of materials such as cartridges, seals, jacks, and requires intense vehicle change (Largo & Garvey, 2018). The negative feature of the extractive production method is the difficulty of transporting the materials used as cutters into the manufactured objects. Thus, it is difficult to create detailed internal structures with this method. Due to these limitations, additional methods to the production of 3D printing

are preferred. The first person to describe the additive manufacturing technique was Charles Hull in the early 1980s, and with additive production the development of 3D printing accelerated. Stereolithography (SLA) used in the first 3D printers was a costly and time-consuming method. In the SLA method, the liquid is hardened by heating with the help of a photopolymer laser. The thickness of the solid layers formed with the help of heat is 0.05 - 0.15 millimeters. Then another layer is formed onto the solid layer with liquid resin (Pham & Gault, 1998). These processes are repeated in order to reduce defects in the surface coating and increase the print resolution. (Ian Gibson, 2015). The resolution can be reached up to 100 nanometers. After the printing process is completed, the resulting product is hardened in an ultraviolet (UV) section. These products are hydroscopic due to their potential to show flexibility in humid environments (Chae et al., 2015). The hardening process with UV rays makes the products more fragile. Despite its restrictive properties, this method is used for medical purposes due to its resistance to autoclavable sterilization.

In 1988, Carl Deckard patented the Selective Laser Sintering (SLS) method (Ventola, 2014). Unlike SLA, SLS uses laser to heat solid dust materials (Hoy, 2013). Laser heating is applied to the product covered with the dust layer to ensure the coating of the layer, and then this process is repeated by forming the powder layer again (Pham & Gault, 1998). The thickness of the powder layers welded by heating can range from 0.06 mm to 0.15 mm. Products created with SLS, which have the advantage of using many materials such as plastic, metal and ceramic, have a fairly wide range of uses. Pre-process heating and post-cooling period increases the need for time in production with SLS (Ian Gibson, 2015). The SLS method requires an experienced specialist due to its internal structure that contains nitrogen and can reach high temperatures (Chae et al., 2015).

The Fused Filament Manufacturing (FFM) printer patent was acquired by Scott Crump and his company in 1992, and Fused Accumulation Modeling (FAM) technique is the most commonly used method today. In this technique, the thermoplastic material is sprayed out of the mouthpiece into a thin layer by heating. After each layer is created, the printing bed is moved to the next layer, subdued by the device thinner than one millimeter. According to other techniques, in this method, which is both easier to use and less expensive, the print resolution varies according to the thickness of the mouthpiece. As the resolution increases, the time increases. (Ian Gibson, 2015). The disadvantage is that only thermoplastic materials can be used. Also, the maximum resolution is less than techniques that can increase the resolution with laser diameter such as SLS or SLA (Pham & Gault, 1998). In 1994, with the addition of 3D printing technologies to the 2D inkjet printer mechanisms, material spraying 3D printers were developed. These printers have been able to place thin layers of resin with advanced technology and then perform rapid hardening process with strong UV rays. These printers can print at a resolution of 0.016 to 0.028 mm and can simultaneously print multiple materials at room temperature (Ventola, 2014) (Chae et al., 2015). Material-spraying printers are more affordable than those containing lasers. There is no support provided by the printing material under the printed product in this method. Therefore, it is necessary to create support in order to be able to print correctly, and these supports must be removed by completion of printing. Thermoplastics and photopolymers can be used as printing materials (Ian Gibson, 2015).

Binding spray printers, which began to develop in 1995, work in a similar way to printers that spray printing materials. 3D printing is done in a dust depot and requires no supporting structure (Chae et al., 2015). With this technique, products with multiple

colors can be printed in one layer. This feature is useful in the production of anatomical models (Ligon et al., 2017). It is a cost-effective and fast production method.

The digital light processing (DLP) method, obtained with the development of SLA technology and produced in 2000, directs light to photoreactive polymers with the help of a series of micro mirrors (Kessler et al., 2020). Photoreactive liquid polymers used as printing materials harden after exposure to light. The resolution of the models produced by this method is proportional to the number of mirrors. Because of the digital projector, the sizes are larger than the SLA. It creates harder surfaces than SLA due to its cornered voxels. This is a quick method because all layers can be printed simultaneously (Zhang et al., 2019).

With the Continuous Liquid Interface technology (CLIP) developed in 2013, the printing method can print faster than DLP. The hardening of the liquid material by the thermal effect is similar to DLP, but the dead area is reduced because it has an oxygen-transmitting membrane and the liquid interface is preserved. Continuity is ensured during the printing process with the protection of the liquid interface. The disadvantage is that this technique is quite expensive.

Materials

The choice of materials is important to produce realistic models. The materials used in 3D printing can be studied in four main heads: polymers, metals, ceramics and composites.

Compared to metals and ceramics, because the melting temperature is low, the cost is reasonable and easy to shape, the polymers are advantageous in work that requires rapid printing. Metal materials are conductive, ceramic materials are insulating. Corrosion resistance in metals is less than in polymers. The polymers are advantageous because of their high strength.

Ceramics are harder than other materials. Composites are manufactured using three groups of materials. Thus, it is intended to bring together the advantages of each. Models produced for medical purposes must have different characteristics depending on the areas in which they are used. Composite materials used in many 3D printing applications today can be produced in different strength, flexibility, durability and cost models. Implants must be corrosion-resistant and adapt to the surrounding tissue.

a. Polymers

Acrylic resins, the first 3D printed material, are used in the manufacture of detailed anatomical models (Zenha et al., 2011). Acrylic resins, often mentioned in literature, are lightweight and durable (Winder & Bibb, 2005). Because acrylic resins are hygroscopic, bending and tilt can occur when exposed to moisture. (Winder & Bibb, 2005). Long-term exposure to UV rays also causes them to deteriorate (Tröger et al., 2008). Polyester ether ketone (PEEK) is used in the manufacture of cranium and orbital implants. This product, which is a thermoplastic material, is highly biocompatible due to its similar characteristics to bone structure. (Lethaus et al., 2014). The PEEK material is resistant to autoclavable sterilization, and techniques such as SLS, which can print at high temperature, are required to be able to model (Schmidt et al., 2007).

Transparent colored polystyrenes are affordable, lightweight and tough. Because of its hardness, the grinding, cutting and gluing processes are relatively easy to apply.

According to Peek, its resistance to heat is quite weak. (Shi et al., 2008). Because it is more rugged than other plastic materials, polystyrenes are fragile to bend. (Ligon et al., 2017). If rubber or polyamide is added to the polystyrene material, the fragility can be reduced (Ligon et al., 2017).

The characteristics of polyamide (PA) models vary depending on the carbon atoms in their chemical structure. (Griehl & Ruestem, 1970). The PA-12 is affordable in terms of acrylic resins, is resistant to autoclavic sterilization, lightweight, corrosion resistant (Leiggener et al., 2009). Substances such as carbon or aluminum can be added to PA-12 to increase its endurance. It is a nylon that is resistant to moisture and water and has a high biological fit tolerance. (Griehl & Ruestem, 1970).

The most preferred polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS) in FDM printers are thermoplastic materials that can be sterilized. The natural structure of these materials, which also have different colors, can be damaged by autoclavic sterilization or dry thermal sterilisation. In both materials, shape changes can be seen in long-term exposure to moisture. No toxic gases are observed during the printing of PLA. PLA has disadvantages such as being biologically biodegradable and absorbable (Zakhary & Thakker, 2017). In the PLA material, the risk of observing inflammatory reaction by the tissues in which it was implanted has been. (Goth et al., 2012). Another advantage of ABS is that it is easy to develop using composite materials to make it more resistant to various stressors such as pressure and heat. (Ligon et al., 2017).

b. Metals

The strength of titanium used in many reconstruction plates and implants can be increased by alloying with aluminum and vanadium. (Hansen, 2008). Compatible with bone tissue, titanium is suitable for sterilization and has the ability to print perpendicularly for better osseointegration (Rotaru et al., 2015). It also shows tolerance for bending and stretching to give proper shape during operation. (Zakhary & Thakker, 2017). It produces radiation during modeling while being less than metal implants such as vitalium or steel. (Zakhary & Thakker, 2017). The radiopaque nature of the metal is important for postoperative evaluation. Today, its use for fixing bone fractures is the gold standard.

The cost of stainless steel is more convenient than titanium and the durability is higher (Zakhary & Thakker, 2017). Steel materials can also be pressed by laser sintering, such as those of titanium. Nickel alloy steels emit radiation during production, causing allergic reactions. Steel materials are alloyed with titanium in order to enhance biocompatibility and make them more durable (Hansen, 2008).

c. Ceramic

Ceramic materials are less preferred in medical 3D modeling than others (Ian Gibson, 2015). Aluminium nitrate, clay, metal oxides, carbs and nitrites are used in ceramic printing. Due to the difficulties of sterilization, the number of models created using a handle is limited. In addition, these models are more fragile and less water resistant. (Mehra et al., 2011). Models made using ceramic materials need to be compressed at the end of the process. This app reduces the volume of 3D models by 12-18%.

d. Composite

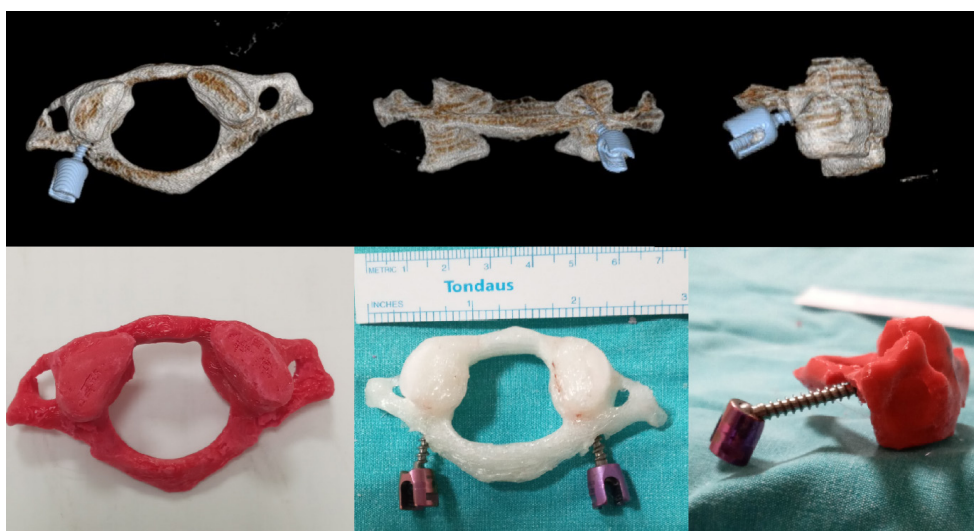
Composite materials that are increasingly used in 3D printers provide high

resolution and durability. According to the characteristics required in 3D models, additional alloys can be made to composite materials. Materials such as nylon and ABS, for example, can be combined with glass and carbon, or resins can be made resistant to combustion with aluminum trihydrate and halogenation. (Ian Gibson, 2015). With this technology, the addition of polykaprolactone, collagen, hydroxyapatite or calcium silicate to bone implants has been studied in order to increase biological adaptation tolerance. In models intended for medical use, the addition of drugs or growth factors for the same purpose is also investigated (Inzana et al., 2014).

In the last half-century, developments in 3D printing technologies have also increased the variety of materials used. In 3D printing applications, it is important to first know the parameters such as model size, the material characteristics required for the model, the reasonable cost, the required time to produce the required number of models. Medical materials produced by 3-dimensional printing methods must be resistant to sterilization exposure more than once and also ensure cost-effectiveness. Manufactured grafts or prostheses for soft tissues should be in line with the biological structure, quality imitating the actual tissue sensation and appearance.

Figure 1

C1 (Atlas) 3D model of the spine created using real patient images and lateral mass screw applied for educational purposes (Computerized Tomography Imaging of Top Series Models, Photos of Sub-Series Models)



Benefits of Use

In a study in which the intraoperative and postoperative characteristics of surgeries performed using 3D models compared to normal operations were studied, it was concluded that perioperative blood loss, duration of the operation, rates of complications and the need for blood transfusion decreased but some increase in healthcare costs. (Madrazo et al., 2009). Furthermore, surgeries using 3D printed models have significant reductions in patients' anxiety-related pain by informing patients that this technology will be used (Guarino et al., 2007).

By contributing of 3D printed models to surgical planning, surgeons can understand parameters in more detail, such as implants to be placed in complex anatomy and the degree of correction required in spinal scoliosis. (Garg & Mehta, 2018). The instruments placed in the 3D printed model guide have higher placement accuracy and

a reduction in pedicular cortex perforation, surgical duration and frequency of use of fluoroscopy has been. (Garg et al., 2019). Thus, in the instruments applied at the cervical level, the damage to the vertebral artery can also be predicted to be reduced. (Lu et al., 2009). With pre-operative planning using 3D-printed models, intraoperative planning and instability conditions were transferred to the preoperative stage, the ergonomics of the surgery was improved, and the duration of the operation was reduced. (Thayaparan et al., 2019). Reduced operating time is to bring with it the reduction in surgical area infections. (Mobbs et al., 2019).

3D models allow visualization of complex pathologies, and the visualized anatomical structures are personal. (Gao et al., 2017). The ability to create patient-specific implants leads to better adaptation of the implants placed, which increases long-term positive functional results. (Walha & Fairbanks, 2021). Predictions are promising, such as the presence of implants that can be customized with 3D printing technologies, the possibility of producing porous implants for more efficient fusion, and that these implants can be processed with released medicines or substances. The possibilities arising with these predictions also shape the future of 3D printing used in spinal surgery. The production of interbody fusion cages and artificial spinal vertebral body implants by using 3D printers increases the production of micro-spinal structures. The use in clinical applications by producing specific implants to each patient's own anatomy can be used in atlantaxial, sacral tumor surgeries and in the treatment of spinal deformities.

Because it is harder to manufacture implants outside of certain geometric shapes by conventional methods, 3D printing of structures in irregular forms will be preferred in the future.

Studies have comparing training with 3D models with 2D methods. Better results were in training areas with 3D models in terms of correct response rates and test times in the tests used in these studies (Brewer et al., 2012) (Berney et al., 2015). In the study of these comparisons, students and assistants preferred to work with 3D sources in a meaningful proportion. (Brewer et al., 2012).

Restrictions on the Use of 3D Medical Printing

1. Time

The time needed for printers to produce 3D models prevents them from being used in diseases that require emergency neurosurgery. (Lan et al., 2016). The 3D printing procedure, which takes half a day even when all technical requirements are met, remains slow in emergencies (Martelli et al., 2016). Although it is known that there are high-resolution devices that can print quickly, studies are needed to show that these devices can be used in brain surgery practice (Xu et al., 2021).

2. Material

There is no established international standard on the choice of materials used in 3D models. Doctors prefer the material based on clinical experience because they cannot choose with reliable markers and experimental evidence (Yan et al., 2018).

3. Property

The cost of the parts created on 3D printers varies depending on the production facilities and materials. It is not possible to high quality standards with every 3D printer

on the market. The cost of installing 3D modeling centers and the need for experienced professional staff make this technology quite expensive in most clinics. When 3D anatomical models are designed, different materials are needed to create different tissues, such as skeleton, muscle, fat tissue or crust. The lack of a single material for soft tissues and skeletal tissues is also a significant cost-increasing limitation.

Time, materials and human resources increase the cost of 3D printing in proportion (Tack et al., 2016).

4. Knowledge and Skill

Although 3D printing methods have increased in research related to clinical applications, the need for quite specialized equipment and trained personnel has prevented their widespread use in clinical practices. (Ashouri-Sanjani et al., 2021). In addition, in the absence of clinical prevalence, it may also be effective that spinal surgeons are unaware of the widespread uses of 3D printing.

The lack of technical knowledge and skills of surgeons about 3D printers has led to a slower adoption of 3D printing methods in medicine. 3D printing methods that do not reach large numbers due to health regulations also have negative effects on their applications in vertebral surgery.

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