3D Printing in Neurosurgery

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6.1 Introduction

3D printing is generating interest in many fields, for example, design, engineering, and medicine. The surgical fields in medicine have taken the lead in progress, especially in orthopedics, maxillofacial reconstruction, and neurosurgery (Eltorai et al. 2015; Yang et al. 2015; Mavili et al. 2007; Müller et al. 2003; McGurk et al. 1997). In particular, 3D printing has contributed greatly to the development of personalized medicine. 3D printing has emerged to play a unique role in the fabrication of personalized implants as well as in surgical planning and simulation, assisting in the consent process, and providing an educational tool for medical students and residents (Mavili et al. 2007; Müller et al. 2003; McGurk et al. 1997; Liew et al. 2015; Jones et al. 2016; Naftulin et al. 2015; Rengier et al. 2010; Webb 2000). This is based on the fact that reasonably complex 3D-printed models can be created in a short period of time with a good cost efficiency.

6.2 Neurosurgery

The application of 3D printing in the field of neurosurgery began in 2007 when researchers started developing implants and plates to reconstruct facial bones and skull defects (Kozakiewicz et al. 2009; Klammert et al. 2010; Li et al. 2013; Zhang et al. 2014). This was an appropriate starting point, as commercially available printers were still in their infancy and only allowed printing in single material and density.

3D printing progressed, following the evidence that models were accurate spatial representations of patient anatomy. By 2012, printers that were able to print in more than one material and density (Shore value) were available. The advent of these new printers allowed researchers and clinicians to create lifelike, spatially, and anatomically accurate models that could be used in the training of surgeons, patient understanding,

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and planning of complex procedures (Narayanan et al. 2015; Tai et al. 2015; Zheng et al. 2016; Ploch et al. 2016).

The aim of this chapter is to trace these developments, the use of the end products, challenges encountered, and future application possibilities.

6.3 Cranial and Facial Implants

In neurosurgery, the initial application of 3D printing technology can be traced to maxillofacial procedures where surgeons reconstructed and or repair of facial and calvarial defects, usually secondary to developmental, traumatic, or postsurgical defects (Solaro et al. 2008; Winder et al. 1999; Dean et al. 2003; Rotaru et al. 2012). The geometry of the facial bones and skull being extremely complex, it is often a challenge to mold plates to accurately fit and provide suitable cosmetic reconstruction (Caro-Osorio et al. 2013; Marbacher et al. 2012; Fathi et al. 2008). Since most of these defects primarily involve underlying bony structures, the application of this technology proved ideal.

Computer-generated images were also used to reconstruct bony defects from a composite using the normal opposite side. This “mirroring,” now commonly used in models that fall in the category of “modified anatomical models,” (Christensen and Rybicki 2017) is not always possible as patients often had bilateral defects. Therefore computer algorithms to mirror or reconstruct from scratch was required. Initial plates used were hand-molded, based on computer graphics (Caro-Osorio et al. 2013; Marbacher et al. 2012; Fathi et al. 2008; Shah et al. 2014).

With the advent of 3D printing, models were initially created in the corrected form, and titanium plates were molded to fit the defect based on the reconstruction. The reconstructed plates were tested on the defect model prior to sterilization and surgery (Solaro et al. 2008; Winder et al. 1999; Dean et al. 2003; Rotaru et al. 2012; D’Urso et al. 2000).

Based on the initial experience learned above, the use of 3D printing for neurosurgical applications was extended to replacing cranial defects. This represented a large need in neurosurgery, as patients often have large segments of their skull removed following severe head injuries as means of controlling rises in intracranial pressure.

Historically, cranial reconstructions were carried out by using the autologous calvarial bone that is removed from the patient during initial surgery and stored in the abdomen of the patient or freeze dried (Shah et al. 2014; Iwama et al. 2003; Grossman et al. 2007; Shoakazemi et al. 2009). These autologous bones had long-term problems including subsidence, disintegration, and infection (Shoakazemi et al. 2009; Gooch et al. 2009). Subsequently the segments of bone removed at the time of initial surgery were stored in freezers and later sterilized and replaced. Unfortunately, in a large number of patients, these plates disintegrated following their reimplantation, creating large defects. In addition to this, patients often experienced pain at the edges of the disintegrated defect. Eventually, the autologous ribs were ruled out, and various metals and acrylic-based products became increasingly used in the reconstruction (Caro-Osorio et al. 2013; Marbacher et al. 2012; Fathi et al. 2008; Shah et al. 2014). These materials required in situ molding during surgery, usually by hand or with minimal equipment. This extended the intraoperative time course and also created a number of problems including poor fit and cosmetic outcome.

When metal plates like titanium were used, these plates had to be cut and bent to fit, often ending up with sharp edges. This posed as a risk to the operating surgeon who could end up with cuts from the sharp edges. These edges and acute angling of the plates can often cause pressure on the skin flap, resulting in pain and breakdown of the overlying skin (Shah et al. 2014; Gooch et al. 2009).

3D-printed cranial implants overcome most of the problems mentioned above. Using the standard printing method described above, a mold of the decompressed segment of the skull can be created and used as the template over which a titanium plate is cut, compressed, and molded to obtain a good fit (Fig. 6.1). This individually prefabricated cranial implant is then sterilized and

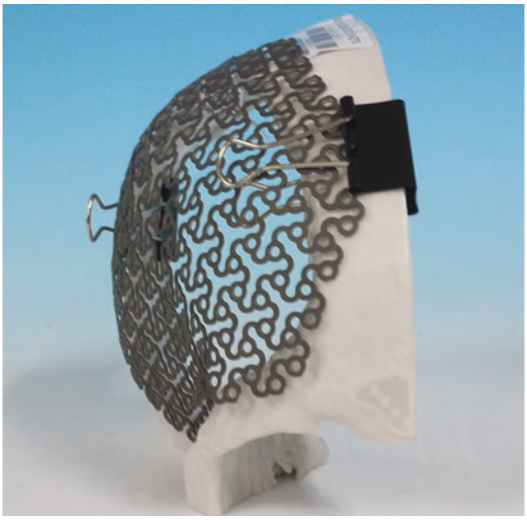

Fig. 6.1 Titanium plate compressed to 3D-printed model of defect

implanted. In addition to titanium, other materials like acrylic and PEEK (Polyether ether ketone) have also been used to create implants using similar techniques (Caro-Osorio et al. 2013; Marbacher et al. 2012; Fathi et al. 2008; Shah et al. 2014; D'Urso et al. 2000; Rosenthal et al. 2014).

Patient's actual bone from the initial decompression cannot be used as a template at the time of implantation simply because often, the patient's skull would have undergone remodeling.

Other surgeons have also directly used 3D-printed titanium plates via the continuous deposition method. This method eliminates cutting and molding; however, these more advanced 3D printing technologies are much more expensive than earlier approaches, and the cost-benefit should be assessed among individual patient presentations (Winder et al. 1999; Dean et al. 2003).

6.4 3D-Printed Models for Surgical Simulation and Training

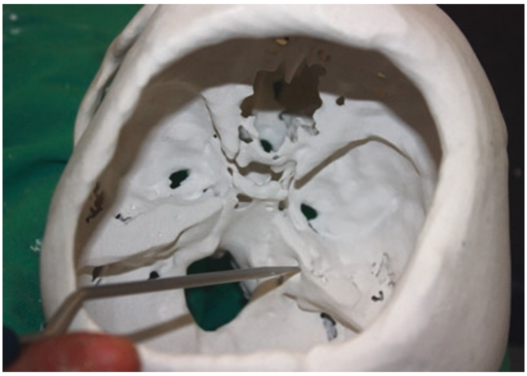

Fig. 6.2 Z Corp, Z Printer 450 printed model of the skull used to confirm spatial accuracy

The first cranial models created were used to understand bone pathology as initial commercial printers like Z Corp, ZPrinter®450 (South Carolina, USA) were only able to print in a single material that mimicked bone very well. The next step involved was in verifying the accuracy of these models both anatomically and spatially. This was performed using standard image guidance navigation stations Medtronic StealthStation®S7™System (Colorado, USA) and BrainLab Kolibri™ (Heimstetten, GER) to register 3D models of a patient's skull to the actual imaging data, thus demonstrating that surgical navigation stations were unable to distinguish the model form the actual patient. We also found all the preselected anatomical points to be spatially accurate (Waran et al. 2012) (Fig. 6.2).

As surgery on an actual patient involves not just the skeletal structures but also various soft tissue components, attempts were made to create a "face" over the facial bones that accurately reflected the patient. Initial attempts were performed using latex poured into a mold. While this technique was able to accurately create the face of a person, the process was labor intensive, and after a period of time, latex had a tendency to contract and crush the underlying "bony structures" (Fig. 6.3).

The next leap in technology was the multimaterial printer. This allowed models to be printed with materials of different density like bone and soft tissue therefore creating multiple interfaces between various tissues (Stratasys Objet500 Connex™). The challenge was to enable the various tissues to interact in an "anatomical or surgical way."

Fig. 6.3 Latex over "bone" model to mimic face

Multi-material printing allowed demonstration of features such as the ability to reflect skin off bone and to allow the bone to be burred or perforated using a standard craniotome, craniotome safety clutch engagement when the bone dura interface is reached and for the dura to be separated from the skull to prevent damage to underlying structures (Fig. 6.4 and Video 1).

Due to these features, we were able to successfully create models based on imaging data from actual patients with pathological findings. Our trainees are able to carry out various standard neurosurgical procedures on these models, such as:

1. Head positioning
2. Registration and planning based on neuro-navigation
3. The ability to carry out standard craniotomies including exposure and removal of simple cortical tumors (Waran et al. 2014a; Waran et al. 2014b)

The advantage of these models as surgical simulators includes the presence of original pathology within the model, as well as supporting data like proper history and medical imaging. All standard surgical equipment used in day-to-day neurosurgery can be used, enhancing the realism of the simulator. These models provide tactile feedbacks that presently do not exist with basic box and complex virtual simulators.

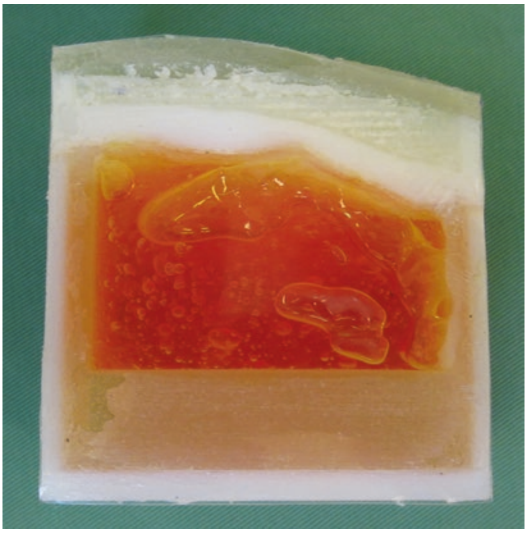

Fig. 6.4 Cross section view of the skin, skull, dura, and tumor

Neurosurgical teaching models currently available include:

- Basic models that allow image guidance registration, flap planning, and bone flap elevation
- Stereotactic models to teach complex stereotactic planning
- Endoscopic models—both for intraventricular (Video 2) and trans-nasal surgery
- Spinal models—cervical and lumbar spine for anterior and posterior approaches (Video 3)

Despite the term multi-material, initial models worked best with one interface and two tissue densities only, for example, bone and skin.

The latest multi-material printers have allowed these models to become more dynamic. Endoscopic intraventricular models can be created with fluid-filled ventricles and intraventricular tumor. Similarly, endoscopic transsphenoidal models can be created with multiple bone ledges, intrasellar tumor, as well as cylindrical tubes cuffing the tumor to mimic carotid arteries (Figs. 6.5 and 6.6a, b).

These models have been used to run "surgical approaches workshops" and training programs for surgeons of various levels from junior trainees to senior surgeons (Narayanan et al. 2015; Waran et al. 2014b; Waran et al. 2015). With the advances in printer technology, future applications include color-printed tissues, tissues with various density, and tactile feedback that allows microdissection and cylindrical structures with pulsatile blood.

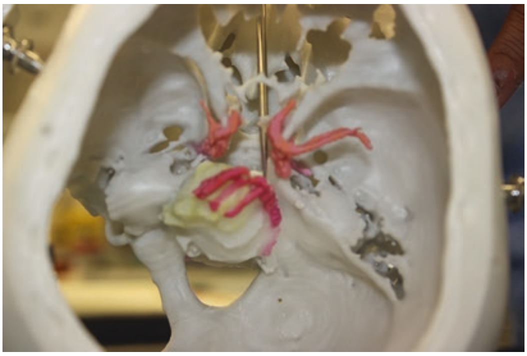

Fig. 6.5 Clival meningioma with circle of Willis

Fig. 6.6 (**a**, **b**) Sagittal and cross-sectional view from tip of nose to sella turcica of a patient with a pituitary tumor and an anterior water bath to mimic CSF leak

6.5 Preoperative and Intraoperative Surgical Simulation

This area has fired the imagination the most in the eyes of the public for the use of 3D printers in customized medicine. 3D printers have in the last 3–4 years been used to preoperatively plan and intraoperatively aid various complex and infrequently performed procedures. They have demonstrated their usefulness in understanding the 3D anatomy of lesions that may differ widely in appearance among individuals with similar problems.

These models have been used in the planning of pediatric neurosurgical-maxillofacial teams performing complex advancement procedures in children with cranial synostosis. Customized patient-based models are useful in the planning of individual bone cuts that are required and assess the degree of advancements that may be required (Poukens et al. 2003; Gateno et al. 2003).

Customized models have also been used in complex base of skull tumors with the aim of assessing the various surgical approaches and corridors (Kondo et al. 2016; Pacione et al. 2016; Oyama et al. 2015).

More recently, these models have been used in planning the treatment of complex vascular pathology. In this instance, the model was used to understand the complex anatomical relationship of the various vessels and related brain tissue (Ryan et al. 2016; Wurm et al. 2011; Thawani et al. 2016).

6.6 Assisting in the Consent Process

3D-printed models have shown great utility for patient consent, greatly enhancing conversations with patients and enabling meaningful explanations of pathology and interventions to patients. Surgeons have used these personally created models with in situ pathology to explain complex procedures to patients and their relatives. The surgical approaches, brain tissue within the corridor of approach, and possible complication are much better explained to a nonmedical personnel by physical models. It presents as an excellent medical aid in the consent process (Liew et al. 2015; Jones et al. 2016).

6.7 Drawbacks of 3D Printing

The main and probably only drawback of the 3D printing technology is time and cost. It requires expertise and time to segment important anatomical components individually before a print can be commenced. Printing time itself has been shortened in certain instances, but nevertheless, the 3D printing of a complex case can take up to a full day. The initial expense of buying a versatile printer and maintaining expert staff to run it is still expensive and may add on to an already escalating healthcare cost, resulting in being prohibitive to be used routinely for all patients. This current technique is therefore most useful for complex, elective procedures requiring detailed preoperative planning (Martelli et al. 2016; Ionita et al. 2014).

6.8 Conclusions

3D printing has progressed in leaps and bounds since the early days of laser-sintering resin models. We are now able to personalize models based on individual patients in an accurate and cost-effective way to help in the surgical process, surgical training, and patient understanding. The redult is that these collective technologies are very useful neurosurgical tools.

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