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3D Printing technology in neurosurgery: A quest for the perfect fit

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Abstract

Introduction 3Dimensional Printing (3DP), also known as additive manufacturing or rapid prototyping, is a technical and industrial revolution that might significantly change the way we live. It is a form of rapid prototyping, which enables the creation of three-dimensional structures from computer-aided design (CAD) data sets. This is physically achieved through an additive layering process. The recent expansion of 3DP technology into the field of neurosurgery has prompted a widespread investigation on its utility. In this paper, we present out experience with 3D printing in neurosurgical practice. We review the current body of literature and analyze its relevance in shaping future of neurosurgery with special focus on Spine surgery. Materials & Methods: A retrospective study was conducted in a tertiary care hospital where 7 patients with Cranio Vertebral Junction anomalies were operated using 3DP assisted prototypes.10 cases of Calvarial defects were offered cranioplasty where in the implants were made using 3DP technology. These cases were compared with historical controls who shared similar profiles as the 3DP assisted group. The objective comparisons were studied. Our results were compared with data from world literature. Attempt was made to list the advantages and limitations of this technology with special reference to spine surgery. Observation& Inference: Our study conclusively proved that use of 3DP in surgeries of complex CVJ anomalies not only helps in better preoperative planning but also improves the ease of surgery and makes the workflow accurate seamless and less time consuming. It makes the procedure and its attendant risks easier to explain to the lay man. In the ultimate analysis it is poised to become an inescapable requirement while planning and executing complex CVJ anomaly surgeries.

Keywords: 3 Dimensional Printing (3DP), Cranio Vertebral Junction (CVJ), 3D Bio Printing (3DBP).

Introduction

We have entered the 4th Industrial revolution. The physical, digital and biological world continues to converge. Factories, robotics, artificial intelligence, augmented reality and 3 Dimensional printing (3DP) have begun to disrupt and reinvent every aspect of the $12 trillion manufacturing industry, creating unprecedented economic opportunities [1]. The Economic Form report of January 2016 predicts that, 65 percent of children today will grow up to work in jobs that don’t exist yet. 50 percent of the knowledge students acquire in the first year of a four-year technical degree will be outdated by the time they graduate [1, 2]. In past industrial revolutions, there was enough time to train and retrain workers. At present, with the exponential rate of technological innovation, this is no longer the case.

3DP, also known as additive manufacturing or rapid prototyping, is a technical and industrial revolution that might significantly change the way we live. This manufacturing method is based on 3D computer models for the reconstruction of a 3D object by the addition of material layers, such as plaster, metal, plastic, and so on [3]. It is a form of rapid prototyping, which enables the creation of three-dimensional structures from computer-aided design (CAD) data sets. This is physically achieved through an additive layering process [4].

It was Charles W Hull in 1980, who introduced the concept of 3D printing as “stereo lithography”. He started selling the first 3D printers for commercial applications in 1988 [5]. At present basic 3D printer is available for less than 500 pounds through Amazon. Within the Health care sector, Surgery, has embraced the 3DP technology most enthusiastically.

The recent expansion of 3DP technology into the field of neurosurgery has prompted a widespread investigation on its utility. In this paper, we present out experience with 3D printing in neurosurgical practice. We review the current body of literature and analyze its relevance in shaping future of neurosurgery with special focus on Spine surgery.

Materials and Methods

This was a retrospective study in which 3D printed patient specific models were used either for pre- operative planning or in preparation of patient specific implants. 7 cases of cranio vertebral junction (CVJ) anomalies were operated where in 3D printed models were utilized for preoperative planning and also used intra operatively, during surgery. Various parameters were recorded and the cases were followed up for 6 months. These cases were further compared with historical controls which included same number of patients sharing similar clinical & radiological profile.

10 cases of cranial vault defect were treated with 3D acrylic Implant for cranioplasty. These cases were also compared with historical controls where the conventional 2D printed images were utilized for management.

Our outcomes and experiences were compared with those available in world literature. Attempt was also made to critically analyze the advantages and disadvantage of 3D printing and gauge its relevance in shaping future of Neurosurgery.

Observation

Table 1: 3D printing for preoperative planning in Cranio vertebral Junction (CVJ) Anomaly

S. No	Nature of Anomaly	Total Cases
1	Bony anomaly	3
2	Vascular anomaly only	1
3	Bony and vascular anomaly	3

Table 2: 3D printing for preparing calvarial implants for cranioplasty

S. No	Region of Calvaria used for 3D Printing	Total Cases	Purpose of placing 3DP Implant
1	Fronto Temporo Parietal		Cosmesis and protection
2	Sub Occipital		Protection

Table 3: Comparison between 3DP assisted surgeries and Conventional 2DP assisted surgeries of CV Junction anomalies

Aspect of Surgery compared	Surgery assisted with 2D Printed Images	Surgery assisted with 3DP Model
Time taken and ease of planning	More Time taken	Less Time taken and easier to plan
Average Operating time	3 hours	2 hours 35 minutes
Average of X-Ray exposures	50	30
Average Blood Loss per procedure	225 mL	175 mL
Operative Complications	1	1
Average Time to explain procedure and risks to patients and relatives	35 minutes	18 minutes
Inputs from the OR assisting team	good	Better and all preferred to have a 3DP Model during surgery

Observed Advantages

1. Complex anatomical relationships, better appreciated on 3D solid models ‘in hand’.
2. 3DP also enabled advance testing of the surgical procedure and also dictated the exact dimensions of hardware that would be required for Instrumentation.
3. 3.Lesser operating time (Conventional surgery for similar CV Junction anomaly without 3DP Guidance took 3hours where- as with 3D P guided surgery took average time of 2 hours 35 minutes).
4. Lesser number of X-Ray exposures and gave added confidence to operating surgeon about the accuracy of screw placement. (6 exposures per screw placement reduced to 4 exposures per screw placement)
5. 3D-printed models proved to be a useful tool for the teaching and training the entire OR Team, assisting in surgery, thereby helping in seamless work flow which also contributed to lesser operating time.
6. Model in hand worked as a ready reference when in doubt during surgery.
7. Found it relatively easier to explain the surgical procedure and risks to patients and relatives before embarking on surgery (Keeping relatives on board is very important to prevent future litigations)

Observed Limitations

1. Not ideal for emergency surgeries as it takes at least 2 days to get the 3DP model
2. Additional cost of 3DP adds on to the overall treatment cost. Since patient outcome data is lacking, one cannot substantiate it as an inescapable requirement.
3. Does not add to any improvement in the existing diagnosis.
4. Limited indication. Not required for routine cases of CVJ Anomalies.
5. In mobile CVJ anomalies there are bound to be small but significant movements of CVJ during positioning of patient (prone, flexion, traction etc.) which may cause mismatch between the 3DP model and “ on table” orientation of spine. Hence it may test the experience and skill of Surgeon, at times, leading to confusion.

Results

Our study conclusively proved that use of 3DP in surgeries of complex CVJ anomalies not only helps in better preoperative planning but also improves the ease of surgery and makes the workflow accurate seamless and less time consuming. It makes the procedure and its attendant risks easier to explain to the lay man. In the ultimate analysis it is poised to become an inescapable requirement while planning and executing complex CVJ anomaly surgeries.

Discussions

3DP is a form of rapid prototyping, which enables the creation of three-dimensional solid structures from computer-aided design (CAD) data sets. This is physically achieved through an additive layering process [6].

Software methods which give the illusion of 3D volumes on a 2D screen can cause problems regarding the viewing angle, depth, and transparency and lighting anomalies. This can lead to orientation difficulty and errors on table. On 8 August 1984, Charles W ‘Chuck’ Hull gave us the world’s first 3D printer [7]. Its success can be judged by the fact that at present a 3D Printer sells in Amazon for less than 500 pounds. From the time of its invention, this technology has the caught the interest of medical community particularly spine surgery. As the digital, physical and biological worlds continued to converge, 3DP technology merged with the biological world giving rise to 3D Bio printing (3DBP). Keith Murphy, Chairman and Chief Executive Officer at Organovo, a US based Company declared that they had created the world’s first fully cellular 3D bio printed liver tissue in April 2013. This technology further found application in the medicine field. This included- Biomodelling, Design and fabrication of customized implants for prosthetic operations, rehabilitation, and plastic surgery. Indications of 3DP have further expanded to fabrication of porous implants (scaffolds) and tissue engineering, fabrication of specific surgical aids and tools, drug delivery and micron-scale medical devices. The use of 3DP also helps in reducing operating time and blood loss [8, 9, 10]. Our results are in conformity with data of world literature.

3DP in cerebrovascular surgery: This technology has found many applications in cerebrovascular surgery. 3DP vascular networks have been utilized to replicate hemodynamics within an aneurysm, thereby helping in practice of clipping procedures and providing a better understand of the vascular pathology preoperatively [11, 1].

3DP in Neuroendoscopic Surgery: 3DP of ventricular system aids endoscopic surgeons in planning ventriculostomy and Tran's sphenoidal endoscopic procedures [13].

3DP IN Spine Surgery: 3DP holds special importance to the spine surgeon, who plans surgery based on 2D images, while on operating table, handles a 3 dimensional human spine, concurrently keeping the 4th dimension i.e. the dynamic functionality of spine in mind. Adoption of 3DP technology in this scenario minimizes risks, reduces operating time, and reduces hospitalization. This ultimately transforms to making the whole management, economical, safe and less stressful for the spine care provider and the receiver. Advancement of technology has led to use of 3D printed patient specific implants. As no two humans are similar, each spine is unique. A perfectly fitting implant is very much desirable.

3DP in Scoliosis: 3DP assumes more & more importance in spinal deformity corrective surgeries. Recognition of complex anatomical structures in scoliosis can sometimes be difficult to grasp from simple 2D radio-graphic views. 3D models of patient's spine' anatomy facilitates this task by allowing the surgeon to get familiarized each patients peculiar anomaly. Getting to know patients' anatomy before entering an OT allows planning the exact approach, helps to predict bottlenecks and even test procedures beforehand.

3DP also plays an important role in the design and production of personalized instruments and surgical guides. Thanks to the availability of sterilisable and biocompatible printing materials. Guides for pedicle screw placement have also been created through 3DP techniques [14, 15].

3DP as a better aid to doctor patient relationship: 3D prints should be used by a doctor to explain to a patient his or her condition. Offering a better understanding of the anatomical problem and the proposed surgical procedure is reassuring to the patient. It produces better treatment outcome by reducing stress and anxiety.

3DP Spinal Orthoses: 3DP external spinal orthoses created using a reverse engineering approach based on 3D scanners, are able to capture the area of interest. This approach allows a seamless fitting to the patient's anatomy and optimization in the selection of the design and materials. 3D Printed scoliosis brace - combines fashion, design, and technology to create a brace far more appealing to patients, and, as a result, far more patient compliant.

3D Bio Printing: 3DBP combines 3DP with biological repair and/or regeneration of bone defects by using a scaffold as a platform for carrying cells or therapeutic agents to the site of interest. Ideal scaffold aims to mimic the mechanical and biochemical properties of the native tissue. This favor's flow of nutrients encourages Osteoconductive cell support and Osteointegration [16, 17].

Bio mimetic 3D Scaffolds: Tissue engineering techniques such as electro spinning, thermally induced phase separation and 3D printing have allowed development of customizable biomimetic scaffolds. Scaffolds can combine synthetic substrates with stem cells, growth factors and/or cytokines to facilitate bone regeneration [18].

Bio printing of Inter Vertebral Disc (IVD): High-density photo cross linkable collagen gels has been developed as a means to patch a punctured disc and maintain disc height, which happens to be a metric of disc health. A composite tissue engineered IVD made from primary ovine nucleus pulposus (NP) and annulus fibrosis (AF) cells suspended in alginate and collagen respectively has been implanted in caudal spines of rats and beagles. They have shown promising results and may soon translate into human use [19, 20].

3DP in Spinal Cord Injury (SCI): The development of biodegradable polymer grafts for surgical implantation after SCI holds promise for therapeutic use. It is poised to solve many problems of SCI therapy, including transplantation of permissive cells, local and sustained delivery of therapeutic agents, and manipulation of axon topography [21].

Rapid prototyping 3DP technologies provide a practical and anatomically accurate means to produce patient-specific and disease-specific models. These models allow for surgical planning, training, simulation and tissue-engineered and transplants. It is helping in manufacture of devices for the assessment and treatment of neurosurgical diseases. Expansion of this technology in spine surgery will undoubtedly serve practitioners, trainees, and patients. Bill Gates rightly pointed out "Never before in history innovation offered promise of so much to so many in so short a time"

3DP as of today remains a highly specialized process that requires significant capital investments in acquiring complex design software, cameras, and the 3D printing machine [22].

3DP in Minimally Invasive Spine Surgery (MISS): MISS poses unique clinical challenges to surgeons. These include small exposure corridors, difficult visualization, minute working spaces, and a steep learning curve coupled with low margin for error [23]. 3DP Bio models can provide MIS surgeons with tactile feedback and facilitate the means to understand complex patient anatomy during the preoperative planning phase. 3DP bio models have the potential to play an important role in the training of new surgeons by simplifying the intricate anatomy and architecture of the spine which cannot be simulated using 2D images. Design, art and science are independent coordinates which provide greatest satisfaction when used & experienced simultaneously. 3DP is a standing testimony to this fact.

3D P is a technology which will soon cease to appear. It will integrate so well with human biology that it will soon become indistinguishable from it. The future in spine care belongs to surgeons with a different mindset. It will include artists, inventors, creative scientists and holistic right brain thinkers. Soon 3DP technology will integrate with other technologies. These newer possibilities will chart the future of disease, including its prevention and management.

Fig 1: Posterior view of CVJ Anomaly with rotatory subluxation

Fig 3: Top down axial view of CVJ anomaly showing the available opening for cerebro medullary junction.

Fig 4: Operative picture of same patient showing exposure of CVJ with bony decompression.

Fig 5: Posterior fixation in the same patient following decompression.

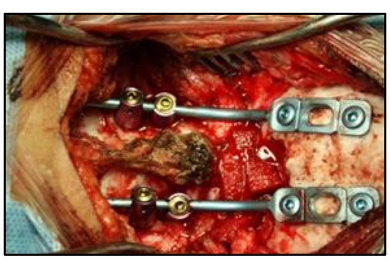

Fig 6: 3DP Model showing CVJ bony and vascular anomaly.

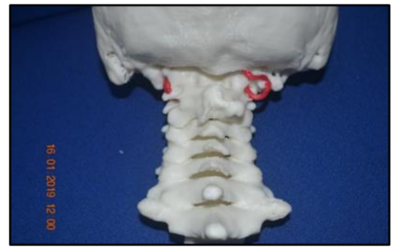

Fig 7: Picture of 3DP model showing bony and vascular CVJ anomaly.

Fig 8: 3DP model showing rotatory anomaly.

Conflict of Interest

None to declare

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