3D Printing Technology-Assisted Endoscopy Surgery in the Treatment of Skull Base Tumors : A retrospective study

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Research

Keywords: 3D printing, skull base tumo, Endoscopy Surgery, Neurosurgery

Posted Date: September 29th, 2020

DOI: https://doi.org/10.21203/rs.3.rs-80038/v1

Abstract

Object 3D printing technology has becoming more and more popular in medicine, we aim to describe the application experiences of 3D printing technology in endoscopic surgery for skull base tumors, with the assessment of 3D-printed models in skull base endoscopic surgery simulation and anatomy learning.

Method Five patients with 3D-printed models were enrolled in our institution from October 2015 to March 2019. 5 individual models, created by different 3D printing methods and printing materials, were used to design the optimal surgical approach before surgery. Besides, the 3D-printed models were applied in endoscopic surgery simulation and anatomy learning. Likert scale questionnaires (1 indicating strongly disagree; 2, disagree; 3, neutral; 4, agree; and 5, strongly agree) were administered to 9 neurosurgeons in our institution to evaluate the application of 3D printed models.

Result We successfully printed 5 cases of complex skull base tumor 3D models and performed endoscopic surgery with the help of information of the 5 3D-printed models. Evaluation of the Likert scores showed that model 4 which was printed by the mixed photosensitive resin material was the most conducive in surgery simulation and anatomy learning. The mean (standard deviation) 3D printing time is 16.3 (4.96) hours, and the mean (SD) printing cost is 4,500 (1183.22) RMB.

Conclusion 3D printing technology has a high value in the application of endoscopic surgery for skull base tumors. The fast 3D printing time can satisfy the requirement of tight preoperative inspection time. Besides, the average price is acceptable for patients and clinical anatomy learning. The combination of the technology of 3D printing and the techniques of skull base endoscopy shows many unique advantages.

1 Introduction

Endoscopic sinus and skull base operations involve an area of complex anatomy, including various central nerves and blood vessels. And the complexity of skull base tumors makes the traditional neurosurgery full of challenges[1, 2]. Last decade, the technique of skull base endoscopy leads the surgery of skull base tumors into the direction of "individualized precision medicine", which has changed the thinking mode of traditional surgery with characteristics of micro-invasive and rapid recovery[3–5]. Advances in endoscopy techniques require neurosurgeons to have the ability to maneuver within a narrow operative field, and the traditional two-dimensional (2D) imaging technique limits the comprehensive understanding of the patient's individualized pathological anatomy[6, 7].

As a revolutionary technology of digital image simulation, 3D Printing is an additive manufacturing method, which, upon receiving computer-aided designs, methodically constructs three-dimensional structures from successive layers. The coupling of stereopsis and tactioception that 3D printing in neurosurgery provides, enhances an awareness of weight, texture, morphology, temperature, and location of the site of interest; this enables surgeons to intuitively understand and analyze the complex tumor anatomy from any perspective[8–13]. Besides, the 3D-printed pathological skull base model can help the patient and his/her relatives to better understand the tumor, to have better communication between doctors and patients, and to avoid the potential contradictions in the current tense doctor-patient relationship in China. What’s more, with advanced 3D printing skull base models, students can use the effective methods to understand the complex anatomy of the head. And neurosurgical residents can have endoscopic simulation-based training to decrease the learning curve[14–18].

Some studies discussed the development of 3D-printed models which can be used in endoscopic skull base surgery, and some studies described 3D-printed physical simulators that are benefit to learning endoscopic techniques[9, 15, 18–21]. However, few studies reported the application experience of 3D-printing technology used in skull base endoscopic surgery. In this article, we printed 5 individual complex patients' skull base tumor models, and with preoperative simulation and surgical planning, we successfully removed the tumors using endoscopy techniques and reducing surgical injuries. Besides, 9 neurosurgeons in our institution evaluated the 3D-printed models with feedback to improve the technique of 3D printing in the skull base area. The study aims to evaluate the 3D-printed models that are used in neuroendoscopic surgery and provide the application experience of 3D printing technology-assisted endoscopy surgery for neurosurgens in detail. And we look forward to the possible research direction of 3D printing technology in neurosurgery in the future.

2 Methods

2.1 Patients

From October 2015 to March 2019, our institution 3D-printed 5 individual complex patients' skull base tumor models, and we successfully removed the tumors by endoscopic surgery with the help of 3D-printed models. Among the 5 patients, there were 3 men and 2 women, with ages from 6 years old to 70 years old. The MRI of patients showed that the largest diameter of the tumor was 8.00 cm, with an average diameter of 5.4 cm. Of the 5 patients, 4 patients had undergone surgical treatment before surgery, which destroyed the original structures of the nasal cavity and skull base and made the complex tumors and their surrounding structures more complicated. Then we communicated with the patients and decided to 3D-printed the skull base tumors before surgery to further recognized the lesions and chose the best surgical approach to avoid surgical risks (Table 1). This retrospective study was approved by the Good Clinical Practice Center of Cancer Hospital, Chinese Academy of Medical Sciences and Peking Union Medical College, and all participants had written the informed consent before the study.

Table 1
the Information of Five Patients with Skull Base Tumors

Patient	Gender	Age (year)	Tumor size (cm)	Surgical result	Pathology	Surgical time (hour)	Blood loss (ml)
1	Male	57	8 × 7	Almost excision	Chordoma	3.5	1000
2	Female	34	5.3 × 4.1	Complete excision	Meningioma	7.9	200
3	Female	57	4.5 × 4	Complete excision	Adenoid cystic carcinoma	3.9	100
4	Male	6	4.1 × 3.5	Complete excision	Primitive neuroectodermal tumor (PNET)	3.2	100
5	Male	70	5.1 × 4.3	Complete excision	Chordoma	6.5	800

2.2 Model Creation

2.2.1 Imaging Data Collection

Patients needed to undergo contrast-enhanced computed tomography (CT) (GE Discovery CT750 HD CT Scanner) and magnetic resonance angiography (CTA) of the head. And the CT examination required the layer thickness ≤ 0.625 mm with all the axial position imaging data. Besides, patients needed to undergo contrast-enhanced magnetic resonance imaging (MRI) (GE Discovery MR 750W 3.0T MRI Scanner). The MRI scan required the layer thickness ≤ 1 mm, and it demanded all the axial, coronal and sagittal imaging data of T1 weighted image(T1WI), T2 weighted image(T2WI), magnetic resonance angiography (MRA), magnetic resonance venography (MRV), fluid-attenuated inversion recovery (FLAIR) and diffusion tensor imaging (DTI). All the original data format was required to be DICOM (Digital Imaging and Communications in Medicine).

2.2.2 Data Processing

Our institution cooperated with Medprin 3D printing company (Medprin Regenerative Medical Technologies Co.Ltd.) and Seine 3D printing company (Zhuhai Seine Technology Co.Ltd.). Medprin 3D printing company used Mimics Medical 17.0 software (Materialise, Leuven, Belgium) to transform the original DICOM image data into 3D images of SLT (stereolithography) format. Then the company used 3-Matic Medical 9.0 software (Materialise, Leuven, Belgium) and Mimics Medical 17.0 to edit the images (For example: grinding and sliding the surface of 3D images, replenishing defective tissues and removing excess parts, etc.). Then Materialise Magics 18.0.3 software (Materialise, Leuven, Belgium) was used to detect SLT data that may affect 3D printing. Medprin used GrabCAD print software (GrabCAD, Massachusetts, USA) to set printing parameters to further refine 3D printing quality, colors and materials. Then, the tumor, skull, blood vessels, nerves and other tissue structures were set to different colors for distinction, and formatted into the corresponding 3D printed anatomy. Finally, the edited 3D model STL files were imported into the 3D printer for printing.

2.2.3 Materials and 3D printers

To optimize the use of 3D printing technologies, clinicians should be aware of the varying strengths and weaknesses of devices and choose a suitable model based on his or her clinical needs. 3D printing materials selection is a crucial part that can determine the hardness and transparency of the 3D-printed models. Researchers can select materials according to the needs of surgical simulation or anatomy learning. The high-resolution, 3D-printed material with rigid quality has previously been used to simulate bone in other 3D-printed models[22]. Transparent resin materials are usually used to analyze the anatomical structure of the tumor and its surrounding nerves and blood vessels. A water-soluble support material is used to create the model to prevent alterations during postprocessing[19].

3D printers are chosen according to the needs of different 3D printing materials and printing fineness. And the 3D printers are needed to print at one time with multiple materials and all colors. Besides, the Medprin 3D printing company requires that the thickness of each 3D printing layer should be less than 0.032 mm.

2.2.4 Model Creation

The SLT files of the 3D-model were imported into the pre-selected 3D printer and been checked whether the 3D model met the printing requirements. If the model was qualified, the manipulator evaluated the printing cost and time then started the 3D printing. After printing, the 3D printed-model was taken out and tested by the company. If different organizations were printed in different modules, they needed to be tested and assembled after printing. And currently, the 3D printed-models were usually printed at one time without module combination, including various colors and materials. The whole 3D printing process is illustrated in **Fig. 1.**

2.3 Model Application

The 3D-printed model, 0° and 30° endoscopes (Karl Storz Endoskope) with video tower, and other endoscopic skull base surgical instruments were prepared for surgical simulation. The 3D-printed model was secured to the operating table with the nasal cavity pointing superiorly to re-create the operating position. During the procedure, the surgeon and assistant started observing the tumor and its surrounding bones, nerves, and blood vessel structures with the endoscope, then the surgeon used highspeed self-irrigating drill, suction tools, curette, backbiter, and other endoscopic skull base surgical instruments to simulate the operation. Figure 2 **and** Fig. 3 showed the endoscopic skull base surgical simulation. After surgical simulation, doctors conduct Multidisciplinary comprehensive discussion according to the 3D-printed models to choose the optimal surgical plan.

2.4 Model Rating

2 associate chief physicians, 4 attending physicians and 3 neurosurgical residents were recruited to evaluate the surgical simulation and anatomy learning feedback of the 5 3D-printed models. A 5-point Likert questionnaire was used for the evaluation (1 indicating strongly disagree; 2, disagree; 3, neutral; 4, agree; and 5, strongly agree).[19] Participants were instructed to provide a Likert scale rating on the 3D-printed models according to the material, color, and softness of models that were used in the surgical simulation and

anatomy learning. The evaluation was based on whether the model could show the anatomical accuracy of the tumor and its surroundings in detail. Besides, the feedback was assessed whether the model was conducive to analyze the patient's disease, and explore the optimal surgical approach and whether the model was beneficial for the surgeon to use the model to explain the condition and pre-operative conversation with the patient and his/her family. statistical analysis was performed using Microsoft Excel (Microsoft Inc).

3 Results

3.1 Model Creation

5 individualized 3D-printed models were created with different materials and 3D printers. The mean printing time was 16.3 (4.96) hours, and the mean cost of the 3D-printed model was 4500 (1183.22) RMB. Three models were processed with Multi-Jet Modeling technology, one model used the stereolithography technology and one model used Seine White Jet Process technology with Multi-Jet Modeling technology. Photosensitive resin materials were widely used in our study. And the specific results were illustrated in Table 2.

Table 2
the Information of 3D-printed Models and the Assessment on Likert Scale

Patient	3D printing company	3D printer	Printing methods	Materials	Printing cost (RMB)	Printing time (hour)	Likert Score mean(SD)
1	Medprin	Projet 660 pro printer	stereolithography	Plaster	3000	20	2.92(0.41)
2	Medprin	J750 full-color printer	Multi-Jet Modeling	Elastic photosensitive resin	4000	18	3.54(0.26)
3	Medprin	J750 full-color printer	Multi-Jet Modeling	Mixed photosensitive resin	4000	18	3.93(0.16)
4	Medprin	J750 full-color printer	Multi-Jet Modeling	Mixed photosensitive resin	5000	19	4.36(0.33)
5	Seine	Seine J501 Pro printer	Multi-Jet Modeling + Seine White Jet Process	Tough photosensitive resin	6500	6.5	4.3(0.21)

3.2 Model Rating

The 5 Models were rated by 9 neurosurgeons in our institution, and neurosurgeons sored models according to the fidelity of surgical simulation and the effect of anatomy learning. The final mean (SD) Likert scores showed that the model 4 printed by the mixed photosensitive resin material obtained the highest mean score of 4.36 (0.33). It meant that among the five cases, the material, color and softness of the model 4 were the most conducive to the simulation and leaning of skull base endoscopic surgery. The mean Likert scores ranged from 3.7 to 4.7 (Table 2).

3.3 Surgery Results

Before surgery, the surgeon planned to perform endoscopic approach to move skull base tumors according to the traditional 2D imaging of CT and MRI of patient 2 and patient 3. However, the 3D-printed models of patient 2 showed that the tumor was located inside and on the saddle, invading the left cavernous sinus and adhering to the surrounding brain tissue. Additionally, patient 2 relapsed after repeated meningioma surgery, then the surgeon decided to abandon the method of endoscopic surgery and switch to the resection of the recurrent meningiomas in the saddle area with the left wing point + longitudinal split approach. The 3D-printed tumors of patient 3 showed that the tumor was located on the right side of the middle skull base and adhered closely to the carotid cavernous sinus segment and the paracranial segment. It indicated that endoscopic surgery was difficult to completely remove the tumor and the surgeon decided to perform the resection of the right middle skull base occupying lesions with the subtemporal approach + temporal bone air space reconstruction + skull base reconstruction + bone flap reduction and fixation. After multidisciplinary comprehensive discussion according to the 3D-printed models, endoscopic approach was finally selected to remove skull base tumors of the other patients.

Intraoperative endoscopy and postoperative imaging examination showed that 4 patients' tumors were completely removed, and 1 patient's tumor was almost completely removed. The mean (SD) intraoperative blood loss of 5 patients was 440 (382.62) ml, and the mean (SD) operation time was 5.00 (1.87) hours. Postoperative pathology showed that there were 2 cases of chordoma; 1 case of atypical meningioma, WHO grade II; 1 case of primitive neuroectodermal tumors (PNETs); and 1 case of epidermoid cyst (Table 1).

4 Discussion

Mankovich, who initially introduced 3D printing to the medical sector, brought the approach to craniomaxillofacial surgery in 1988. Since its introduction to neurosurgery in 1999, 3D printing had illustrated its ability to aid coiling and clipping procedures, tumor biopsies, tumor resections, and implantations in neurosurgery[23–25]. In the last decade, 3D printing technology made this invention specifically appealing in neurosurgery, and some 3D simulators were successfully printed to practice endscopic surgery and learn the anaomy[15, 26]. However, few studies reported the technology in the field of skull base with patient-specific pathologic features.

The anatomy of the skull base is complicated with tumors of various pathology, and skull base surgery is not an easy procedure. As a specialty of neurosurgical oncology, our institution treats a large number of patients with skull base tumors which are complex and diverse every year. Whenever we treat patients with complex tumors in a dangerous skull base, we make efforts to reveal the mask of the tumor and its surrounding bones, blood vessels, and nerve structures in as much detail as possible. Therefore, we actively explore the cutting-edge technology and choose to use 3D printing technology to print complex skull base tumors and their adjacent structures in real-time and three-dimensionally, and we try to select the best surgical plan to reduce surgical injury with the help of the 3D-printed models[26–28]. After communication with patients and their families, we find that the use of 3D printing technology to assist in the treatment of complex skull base tumors is also the demand of patients and their families, because the 3D-printed models can help them who lack of clinical knowledge to understand the complex anatomy and the surgery of the tumor. And it is beneficial to alleviate the tense situation between doctors and patients in China.

Our institution, as a hospital for standardized training of residents, undertakes a large amount of anatomy and surgery teaching work. However, the complex anatomical structures of neurosurgery often puzzle residents who are fresh to this field, especially in the skull base area. Although cadaveric heads are good specimens for anatomy learning, it lacks a pathological anatomical structure. And with the improvement of the management of corpse utilization in China, cadaveric heads are not easy to obtain and are expensive. During clinical teaching, we found that it is an urgent requirement for young neurosurgeons to understand the patient's pathological anatomy and practice endoscopic surgical operations. However, due to the limitations of the operation time and the high workload of the operating rooms, real-time surgery teaching is not an ideal way for students. The surgical simulation learning method based on the 3D-printed models is a better choice for students with the help to improve the key surgical techniques and satisfy the desire for knowledge[29–31].

Due to our early experience in 3D printing, we choose to cooperate with two 3D printing companies to use different 3D printing technologies to print patients' pathological models, and to make a full comparison and feedback evaluation. According to the comparison results of 5 cases of 3D models, we find that the mean (SD) 3D printing time is 16.3 (4.96) hours, the fastest printing time is 6.5hours and the mean (SD) printing cost is 4,500 (1183.22) RMB. It means that the fast 3D printing time could satisfy the requirement of tight preoperative inspection time. Besides, the average price is acceptable for patients and clinical anatomy teaching. Among the 5 models, 4 models use Multi-Jet Modeling 3D-printed technology, 4models choose photosensitive resin materials for printing, which obtain good evaluation feedback results. It may indicate that Multi-Jet Modeling technology and photosensitive resin materials have become the mainstream of 3D printing clinical applications in China. From the results of the model rating, the selection of appropriate printing materials, printing fineness, module transparency and their combinations are vitally important for surgical simulation and anatomy learning, which provides valuable experience for the clinical application of 3D printing technology in our institution.

The combination of the technology of 3D printing and the techniques of skull base endoscopy shows some unique advantages:

1) The 3D-printed skull base tumor models have the ability to combine CT, MRI and other imaging data to display the anatomical structures point-to-point and three-dimensionally, which the original two-dimensional imaging technology has not and can not provide realistic tactical sensation[32].

2) The 3D printed models can help neurosurgeons to have surgical simulation to select the entry point and make the optimal surgical plan. With the help, surgeons might anticipate possible dangers during the operation and prepare corresponding solutions in advance[25, 33, 34].

3) 3D printed models can assist neurosurgeons to decrease the learning curve of skull base endoscopy and improve the efficiency of skull base endoscopy surgery teaching and training. Currently, most simulations of skull base surgery are based on animals, cadaveric head or plastic molds, however, these methods lack realism and most are neither convenient nor practical for daily rehearsal[15, 35–37].

4) For patients and their families who lack medical knowledge, the 3D printed models are a good medium to enhance the communication with surgeons before surgery[25, 38].

5) 3D printing technology and skull base endoscopy technique will improve and develop with each other.

However, there were some limitations in our study: **1)** the application of 3D printing technology in the field of skull base tumor endoscopic surgery was mostly reported by some cases at present. Therefore, the long-term impact and effect of improving the safety of surgery and preoperative training would need more studies. **2)** there were only 5 3D-prinded models in our study, and we would enroll more cases to draw more objective and reliable conclusions. **3)** The study was in part based on a subjective Likert scale, which was subject to response bias, especially given our small sample size, but we decided to conduct a prospective cohort study to analyse the advantages of 3D printing technology used in endoscopic surgery for skull base tumors. And Likert questionnaires werecommonly used to evaluate simulation models[19, 21, 39]. **4)** Future studies with a larger sample size, more different print materials and printing methods should be used and analyzed, combining with better endoscopic techniques.

With the development improvement of 3D printing technology, we assured that the 3D-printed models would be more accurate and realistic for simulation. We believed that the texture, color and substance of 3D-printed models would gradually become more realistic, and nerve fibers and other subtle anatomical structures would become clearer and more accurate. Sophisticated sensors, blood, cerebrospinal fluid simulation and other high technology would be created and applied, which would make the simulation as real as the operation scene[29].

5 Conclusion And Perspectives

This study successfully printed five 3D models with patient-specific pathologic features, and with the surgical simulation and multidisciplinary comprehensive discussion, the surgeon selected the optimal surgical plan and reduced the surgical complications. The study provided the application experience of 3D technology with 3D printing steps, materials and methods and showed some unique advantages combined with techniques of skull base endoscopy. We believed that 3D printing technology would paly a more significant role in surgical training, anatomy learning and preoperative planning, especially in the complicated skull base areas.

This work was supported by Application Research and Achievement Promotion of Clinical Characteristics in Beijing (No. Z161100000516118).

Declarations

Ethical Approval and Consent to participate

This retrospective study was approved by the Good Clinical Practice Center of Cancer Hospital, Chinese Academy of Medical Sciences and Peking Union Medical College, and all participants had written the informed consent before the study.

Consent for publication

This manuscript hasn't been published before and is not being considered for publication elsewhere. All the authors have contributed to the creation of this manuscript for important intellectual content and read and approved the final manuscript.

Availability of supporting data

Materials and data will be available with reasonable request.

Competing interests

We declare that there is no conflict of interest in the study.

Funding

This work was supported by Application Research and Achievement Promotion of Clinical Characteristics in Beijing (No. Z161100000516118).

Authors' contributions

Dr. Peng Gao was the main writer of the manuscript. and Dr. Angsi Liu and Dr. Fuxing Zuo were responsible for data collection and contributed to revise the manuscript.

Dr. Jianxin Kong and Dr. Xueji Li were the main surgeons for the study.

Acknowledgements

Not applicable

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Figures

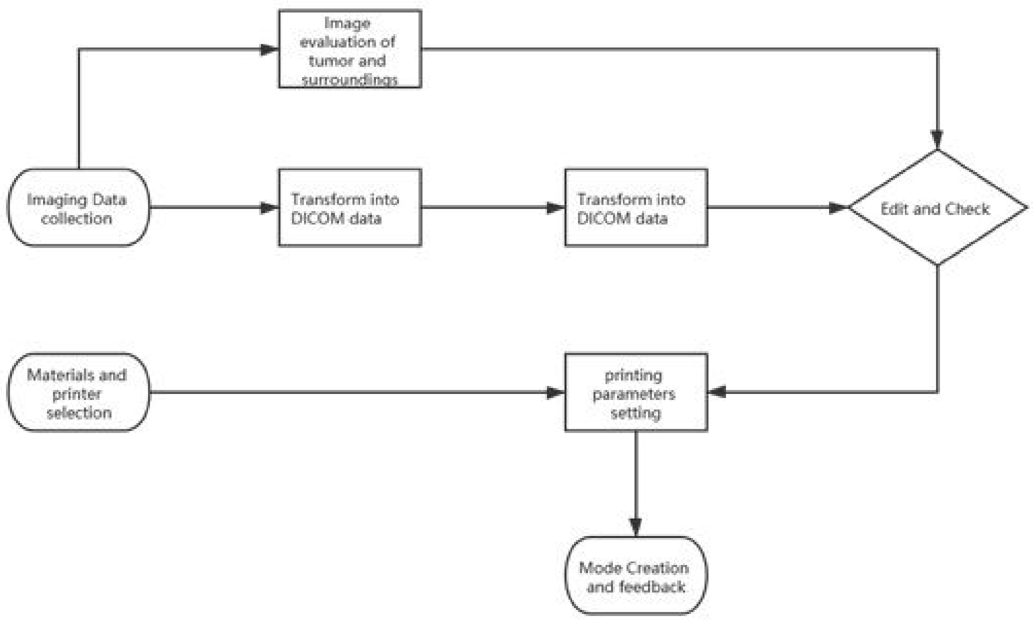

Figure 1

Procedures of 3D Printing Skull Base Tumor Models with Application and Feedback

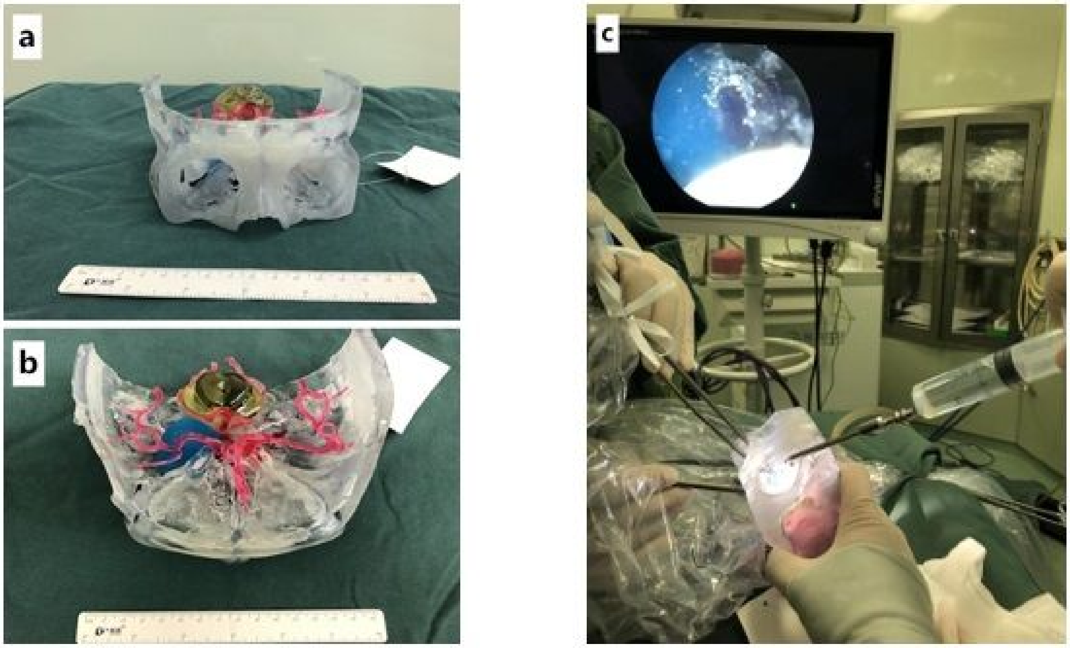

Figure 2

3D-printed model 2 with the simulation to make the optimal surgical plan in the operation room. (a) (b) Anterior and superior views of the 3D-printed model 2 with pathologic entities. (c) The surgeon was trying to electrocoagulate the blood vessel around the tumor with the bipolar coagulation forceps. With the help of surgical simulation and the multidisciplinary comprehensive discussion, the surgeon decided to abandon the method of endoscopic surgery and switch to the resection of the recurrent meningiomas in the saddle area with the left wing point + longitudinal split approach.

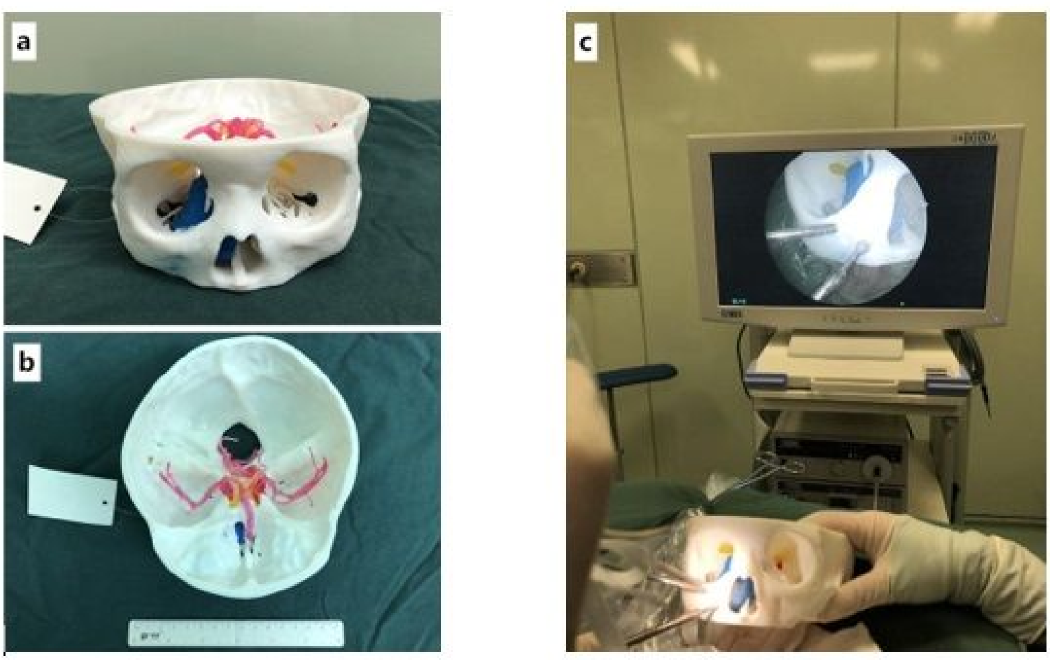

Figure 3

3D-printed model 2 with the simulation to make the optimal surgical plan in the operation room. (a) (b) Anterior and superior views of the 3D-printed model 2 with pathologic entities. (c) The surgeon was trying to electrocoagulate the blood vessel around the tumor with the bipolar coagulation forceps. With the help of surgical simulation and the multidisciplinary comprehensive discussion, the surgeon decided to abandon the method of endoscopic surgery and switch to the resection of the recurrent meningiomas in the saddle area with the left wing point + longitudinal split approach.