ISSN 2616-5791 Vol.3, Issue 3: 44-53, DOI: 10.25236/AJMHS.2022.030309

A 3D printing method of customized magnetic focusing generator for magnetic field therapy

Chao Yang[1], Yunhan Tian[2], Jinhua Yu[1], Minde Jin[2], Ning Xie[2], Yinhui Deng[1,3,*]

[1]*Biomedical Engineering Center, School of Information Science and Technology, Fudan University, Shanghai, 200433, China*
[2]*Shanghai Fuzhi Information Technology Co. Ltd., Shanghai, 200438, China*
[3]*Shanghai Mingge Information Technology Co. Ltd., Shanghai, 200438, China*
[*]*Corresponding author: yinhui.deng@minggecn.com*

Abstract: *As one of the most malignant tumors, brain tumors seriously threaten people's health. Traditional treatment methods, such as surgery combined with radiotherapy and chemotherapy, will bring great side effects and high treatment costs. As a new type of brain tumor treatment method, magnetic field therapy has the advantages of well effectiveness, non-invasive property and relatively low treatment cost. However, it has the disadvantage that magnetic field energy cannot effectively focus on tumors, especially when facing the differences of brain tumors among different patients. This may lead to side effects similar to those caused by traditional chemotherapy methods that cannot focus on tumors. For this, a 3D printing method of customized magnetic focusing generator for magnetic field therapy is proposed in the paper. First, a state-of-the-art 3D-Unet artificial intelligence model is used to segment the magnetic resonance imaging (MRI) data of patients to obtain the spatial information of brain tumors and personalized patient skulls. Then, through the design of the hemispherical solenoid array model, the multi-dimensional simulation and actual measurement of the magnetic focusing mode are carried out to obtain a solenoid focusing scheme that gives consideration to both magnetic focusing and energy efficiency. Finally, based on high-precision 3D printing technology, 3D reconstruction is carried out for the spatial information of brain tumors and personalized patient skulls with the solenoid focusing scheme. The magnetic field generator is thus obtained based on customized 3D printing. The device not only fits the patient's skull and is suitable for wearing, but also can accurately control the spatial information related to the tumor, so that the magnetic field energy can accurately focus on the brain tumor area of specific patients to achieve accurate magnetic field treatment. Through the experiment, the actual measurement of the magnetic field distribution generated by the device is carried out and compared with the simulation results. While the magnetic focusing is verified, the error between the measurement and simulation reaches only 2.2%, which verifies the feasibility of the overall method. The customized magnetic focusing generator proposed in the paper is expected to provide a new and effective clinical approach for the treatment of brain tumors.*

Keywords: *Brain tumor, Magnetic focusing, Artificial intelligence tumor segmentation, Solenoid array, 3D printing*

1. Introduction

Brain tumor is a common primary intracranial tumor. Because of its high heterogeneity, the 5-year survival rate is less than 5%, which is second only to pancreatic cancer and lung cancer in all over the body. The treatment of brain tumors is mainly surgical resection, supplemented by chemotherapy and radiotherapy. In the process of chemotherapy and radiotherapy, not only the cost is high, the efficiency is low, but also the other healthy tissues of patients will be negatively affected. In clinical practice, sometimes due to the poor physical condition of patients, the dosage of drugs will be reduced, and treatment will be delayed or even stopped. Therefore, it is of great significance to explore a treatment method with small side effects and low cost.

In recent years, magnetic field has been proposed as a novel treatment method, which has the advantages of less side effects, high efficiency, wide application, low cost and non-invasive. In the 1970s, Weber et al. [1] verified that the non-uniform magnetic field is an effective inhibitor of tumor cell vitality and growth rate in vitro and in vivo. In addition, cancer cells such as fibrosarcoma [2] have been proved to be inhibited by static magnetic fields (SMFs) and low-frequency magnetic fields (LF MFs, frequency

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lower than 300 Hz). In 2017, Ulasov et al. [3] verified the precise knockout of EGFR gene expression by radio frequency electromagnetic energy. Many experiments have confirmed that magnetic field can fight against tumors by inhibiting the growth and proliferation of tumor cells and inducing cycle arrest. However, the failure of magnetic field energy to focus on tumors may cause side effects similar to those caused by the failure of traditional chemotherapy methods to focus on tumors. Therefore, it is an urgent problem to find a way that can focus the magnetic field on the tumor area.

For the work related to magnetic field focusing, in 1990, Ueno et al. [4] constructed an 8-shaped coil placed outside the head to generate a time-varying magnetic field while bypassing the target in the opposite direction and passing through the head. In 1994, Roth BJ et al. [5] designed a four-leaf magnetic coil to stimulate peripheral nerves in vitro. In 2005, Wang et al. [6] studied the focusing property of 8-shaped coil and quadrangle coil, and found that quadrangle coil has better focusing property. In 2004, Liu et al. [7] designed planar and toroidal coil arrays and optimized them to achieve magnetic focusing. In 2013, Yan et al. [8] proposed a spherical focusing coil array and optimized the model to obtain good focusing performance. Although the above researchers have improved the focusing ability of the magnetic field to a certain extent, their work are basically in the theoretical level and lack of verification of the effectiveness of the coil structure. Therefore, designing a magnetic focusing model and customizing devices for patients is still an urgent and important direction in the research of magnetic therapy.

This paper innovatively proposes a 3D printing method of customized magnetic focusing generator for magnetic field therapy. First, the Unet artificial intelligence model is used to segment the patient's magnetic resonance imaging (MRI) data to obtain the spatial information of the patient's tumor and skull. Then, based on the hemispherical solenoid array, the magnetic focusing model is established, and the solenoid focusing scheme is obtained through simulation and measurement. Finally, high-precision 3D printing technology is used to customize the magnetic field generator for patients to achieve accurate magnetic field treatment. In this paper, the magnetic field distribution generated by the device is simulated and measured through relevant experiments to verify the feasibility of the overall method.

2. Method

For brain tumors, the traditional treatment is surgical resection combined with chemotherapy. Due to the differences between patients and the inability of chemotherapy to focus on the tumor area, other healthy tissues of patients are often damaged during chemotherapy. In order to avoid side effects similar to chemotherapy caused by magnetic field therapy, the key to magnetic field therapy is to obtain the spatial information of the patient's tumor and focus the magnetic field on the patient's tumor area.

2.1 Patient tumor segmentation

With the continuous development of artificial intelligence, image segmentation is making progress. Medical image segmentation is an important part of image segmentation. In recent years, many researchers have proposed many segmentation algorithms. In 2014, Long et al. [9] proposed a full convolutional neural network (FCN) based on the traditional convolutional neural network (CNN), and achieved pixel level classification in the field of image segmentation. In 2015, Ronneberger et al. [10] proposed Unet model on the basis of FCN and added residual connection structure, so that the low-level feature information of the image extracted by the network in the encoder stage and the high-level feature information of the image extracted in the decoder stage can be fused, so that the network can learn the features lost due to down sampling in the encoder stage, thus improving the segmentation accuracy of the network. Since then, many algorithms have been improved based on the Unet model and achieved well results, such as attention Unet [11], res-Unet [12], nn-Unet [13], Unet++ [14], etc.

Fig. 1 shows the 3D U-net model [15] framework structure applied in our method. The model is divided into two parts: the encoder and the decoder. The encoder passes the image or extracted features twice by the convolution of $3\times3\times3$. Each convolution is followed by a rectified linear unit (ReLU) processing, which is followed by a $2\times2\times2$ pooling. The encoder passes the previous feature map once with a $2\times2\times2$ up-sampling. After sampling, the features extracted from the encoder are combined with the output and then the combined features are processed twice by the convolution of $3\times3\times3$. After each convolution, there is a ReLU processing.

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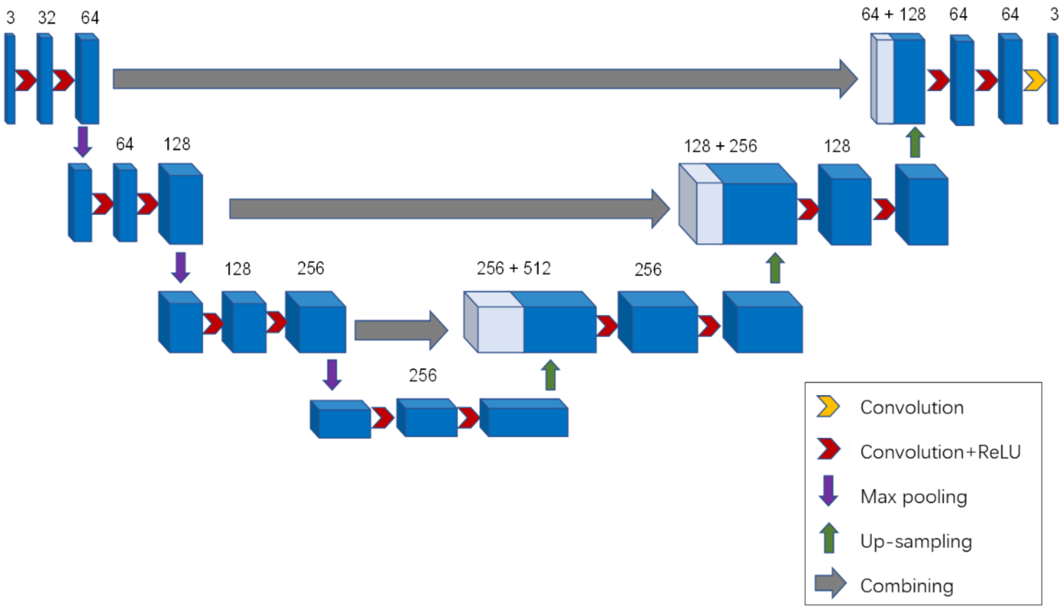

Figure 1: 3D Unet model structure for segmentation

We apply the 3D Unet model as a segmentation network which is developed in PyTorch and trained from scratch. The dataset used is BraTs2018 [16]. The BraTs2018 dataset contains 285 training data. Each data contains four MRI modes of the same patient which are flair, T1, T1c and T2. The tumor segmentation results of each patient are also available. We utilized each of the four modes of each patient in the network for training, and then used the trained network to predict the tumor location of the patient in the actual case. Fig. 2 demonstrates one example of the segmentation result of the tumor.

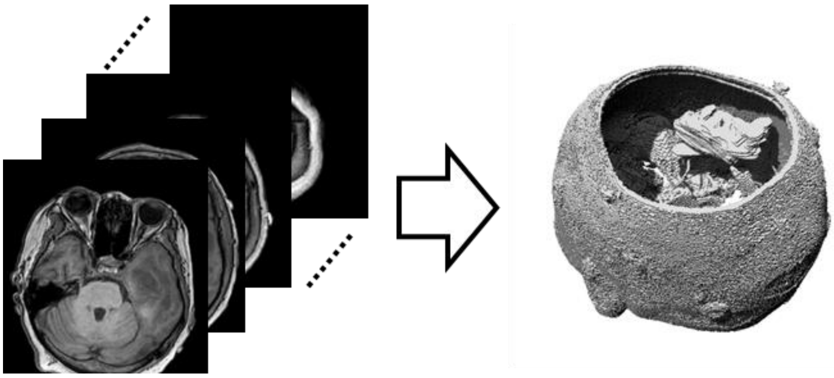

Figure 2: MRI data segmentation results of tumors

2.2 Patient skull segmentation

To obtain the spatial information of the tumor, it is necessary not only to segment the tumor, but also to determine its relative position with the skull so as to determine the focus center of the magnetic field generator. SPM12 is a software package for brain imaging data sequence analysis, which can be used for data analysis such as MRI images. The software can separate gray matter, white matter, cerebrospinal fluid and skull from human brain MRI data. In this paper, SPM12 in MATLAB tool kit is used to analyze the patient's MRI data and the function of tissue segmentation in SPM 12 is used to separate the patient's skull from the MRI data.

2.3 Three-dimensional reconstruction of tumor and skull

3D Slicer is an image analysis and processing software funded by the National Academy of Sciences and jointly developed by MIT and Harvard University [17]. It is widely used in neurosurgery clinic practice because of its convenient operation and certain expansion of functions [18]. 3D slicer software can perform 3D reconstruction of MRI, CT and other imaging data. The diseased area of patients and their surrounding tissues in the form of 3D models can be visualized. Meanwhile, the reconstruction

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models are saved in STL format for 3D printing and the models for doctors can be printed to intuitively understand the patient's situation.

We import the patient's original MRI data file into the 3D slicer and then import the segmented patient's tumor and skull files. The tumor and skull files are loaded into the 3D slicer as "segmentation". Finally, show-3D function is opened to view the 3D view of the patient's tumor and skull and export the 3D file to STL format for subsequent 3D printing, as shown in Figure 3.

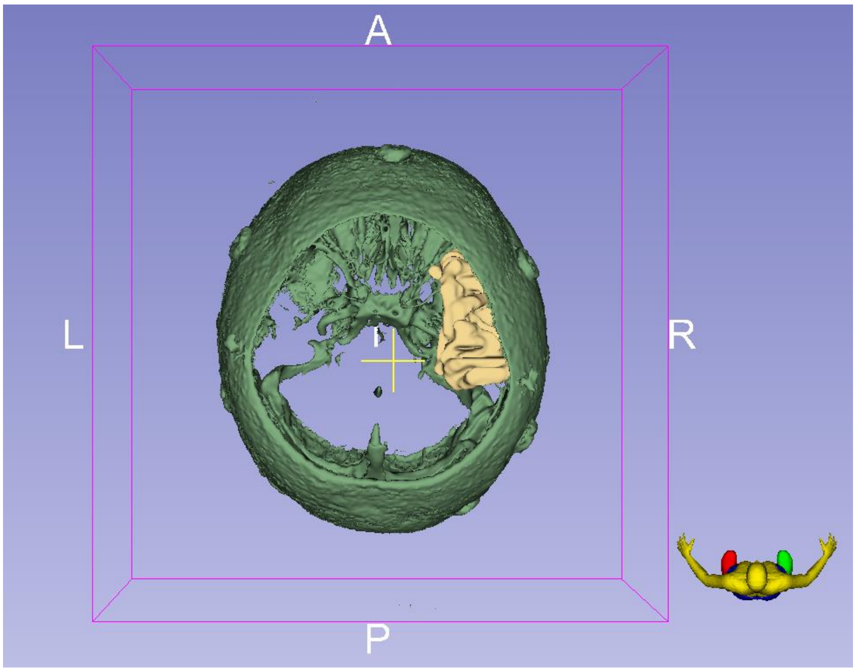

Figure 3: Three-dimensional reconstruction of tumor and skull

2.4 Focusing method on magnetic field energy of solenoid array

The definition of the magnetic focusing refers to that in a certain area, the minimum value of the magnetic field reaches the predetermined requirements, and the difference between the magnetic field strength in the focusing area and the one outside the area is relatively large. Based on the spherical coil array designed by Miyan et al. [8], this paper designs a hemispherical solenoid array to explore the best solenoid focusing scheme and finally apply it to actual patients.

As shown in Fig. 4, the solenoid array consists of 40 points, from the inside to the outside, which are the center point, the first circle, the second circle, and the third circle. Eight points are equally spaced in the first circle, marked as 1.1~1.8 respectively, 16 points are equally spaced in the second circle, marked as 2.1~2.16 respectively, and 16 points are equally spaced in the third circle, marked as 3.1~3.16 respectively. The straight line of the line segment formed by each point and the hemispherical center is the central axis of the solenoid at each point. In addition, the included angle between the central axis of the same circle of solenoid and the Z axis is the same, which is 22.5°, 45° and 67.5° respectively. The number of windings, radius and current in the solenoid can be selected as needed. When a current is applied to the solenoid in the array, a magnetic field can be generated. A circular area with a radius of 50mm is selected in the x-y plane as the focus area. The selection of parameters of different solenoids and the selection of points will affect the focusing situation in the focusing area. Therefore, it is crucial to explore the selection of solenoid parameters and the selection of appropriate points for magnetic focusing.

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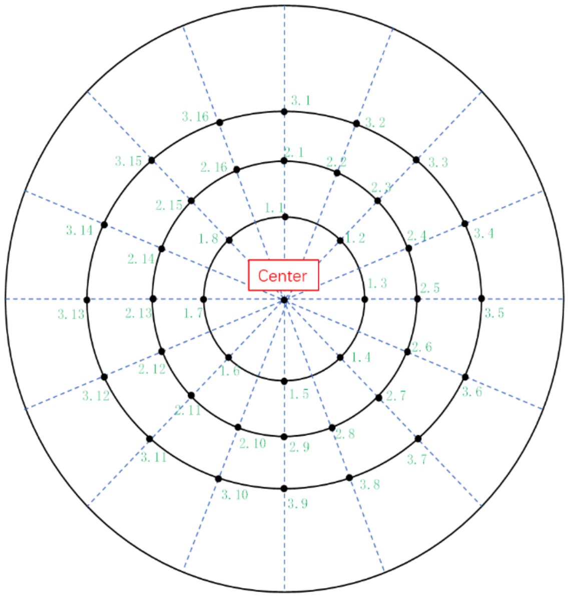
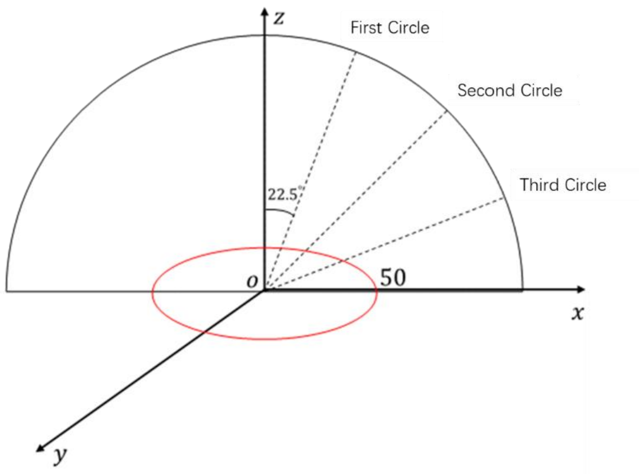


(a)



(b)

(c)

Figure 4: Apparatus for focusing solenoid. (a) Spatial description of the device; (b) Structure angle diagram of the device; (c) The practical picture of the built device.

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2.5 Customized magnetic therapy device for patients based on 3D printing

According to the 3D files of the patient's tumor and skull, the 3D model of the patient's tumor and skull can be obtained. Then the helmet structure for a specific patient can be determined. Firstly, it can fully fit the patient's head. Secondly, it can accurately control the relevant spatial position for the device, the skull and the tumor. According to the defined focusing method, the specific location of the solenoid can be determined on the helmet structure. Therefore, when the patient wears such device, the magnetic field energy can be accurately focused on his or her specific tumor area.

In order to realize the customized magnetic therapy device for patients, we use the 3D printer of Fuzhi Company (Raise3D high-precision FFF printer). According to the related 3D data, we use the bio-safe, ultra-light, non-screen magnetic field material (P-filament 721 Natural Polypropylen) for high-precision printing so as to realize the 3D printing of the customized magnetic therapy device for patients.

3. Experimental Results

3.1 Experiment of magnetic focusing modes

The experiments hear were performed to explore the optimal solenoid parameters as well as solenoid spatial placements. The focus area is a circular area with a radius of 50mm in the x-y plane, as shown in Fig. 5.

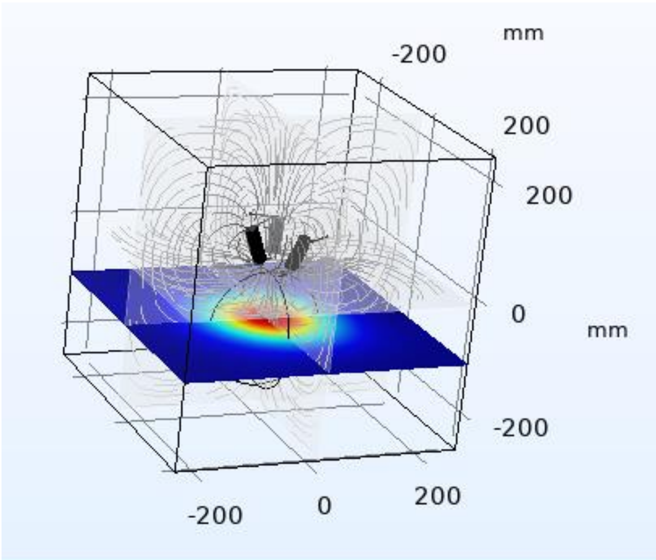

Figure 5: Magnetic focusing experimental area

For solenoid position and solenoid parameters, we designed solenoid space position experiment and magnetic field distribution experiment respectively to study solenoid placement position and solenoid parameter selection. Table 1 shows the values of solenoid space position experimental variables and Table 2 shows the values of magnetic field distribution experimental variables.

Table 1: Variable values of solenoid space position experiment

Index	Number of solenoids	Position of solenoids	Number of windings	Current
1	3	1.2, 1.5, 1.8	40	1A
2	3	2.2, 2.5, 2.8	40	1A
3	3	3.2, 3.5, 3.8	40	1A
4	5	Center, 1.2, 1.4, 1.6, 1.8	40	1A
5	5	Center, 2.2, 2.4, 2.6, 2.8	40	1A
6	5	Center, 3.2, 3.4, 3.6, 3.8	40	1A

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Table 2: The values of experimental variables for magnetic field distribution

Index	Number of solenoids	Position of solenoids	Number of windings	Current
1	3	1.2, 1.5, 1.8	20	0.5A
2	3	1.2, 1.5, 1.8	40	0.5A
3	3	1.2, 1.5, 1.8	80	0.5A
4	3	1.2, 1.5, 1.8	20	1A
5	3	1.2, 1.5, 1.8	40	1A
6	3	1.2, 1.5, 1.8	80	1A
7	3	1.2, 1.5, 1.8	20	1.5A
8	3	1.2, 1.5, 1.8	40	1.5A
9	3	1.2, 1.5, 1.8	80	1.5A

COMSOL Multiphysics [19] is a multi-physical-field direct coupling simulation software introduced in China in recent years. It can express complex problems in the form of differential equations, partial differential equations and other equations and solve the equations with finite element method. In addition, COMSOL Multiphysics also has relatively strong visualization capability. It has a special magnetostatic field solution module for magnetic field simulation. After establishing a geometric model and setting relevant parameters such as material properties, the calculation results can be presented in one-dimensional, two-dimensional or three-dimensional forms.

According to the variable values in the table and the solenoid position, the solenoid array model is established in COMSOL Multiphysics, as shown in Fig. 6 for solenoid 1.2, 1.5 and 1.8. The different magnetic field distributions are calculated in the solenoid space position experiment and the results of different magnetic field distributions are shown in Fig. 7. When the solenoid positions are 1.2, 1.5 and 1.8, the magnetic focusing effect is well. Therefore, the solenoid positions of 1.2, 1.5 and 1.8 are selected for the following magnetic field distribution experiment. The relevant simulation results are shown in Fig. 8. Compared with the simulation results, the error of all measured results in the experiment is 4.3%, which shows the effectiveness and accuracy of the simulation of magnetic field.

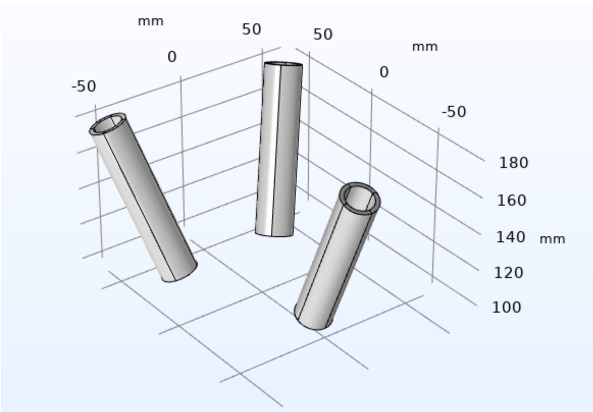

Figure 6: Solenoid positions of 1.2, 1.5 and 1.8

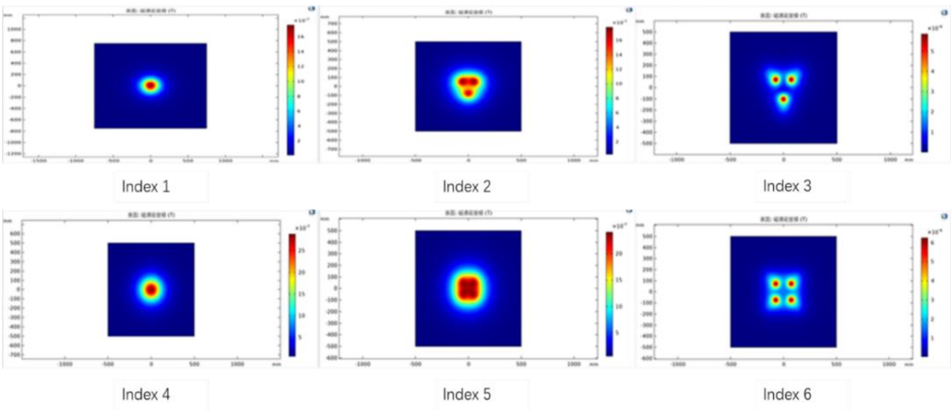

Figure 7: Distribution of magnetic field in solenoid spatial position experiment

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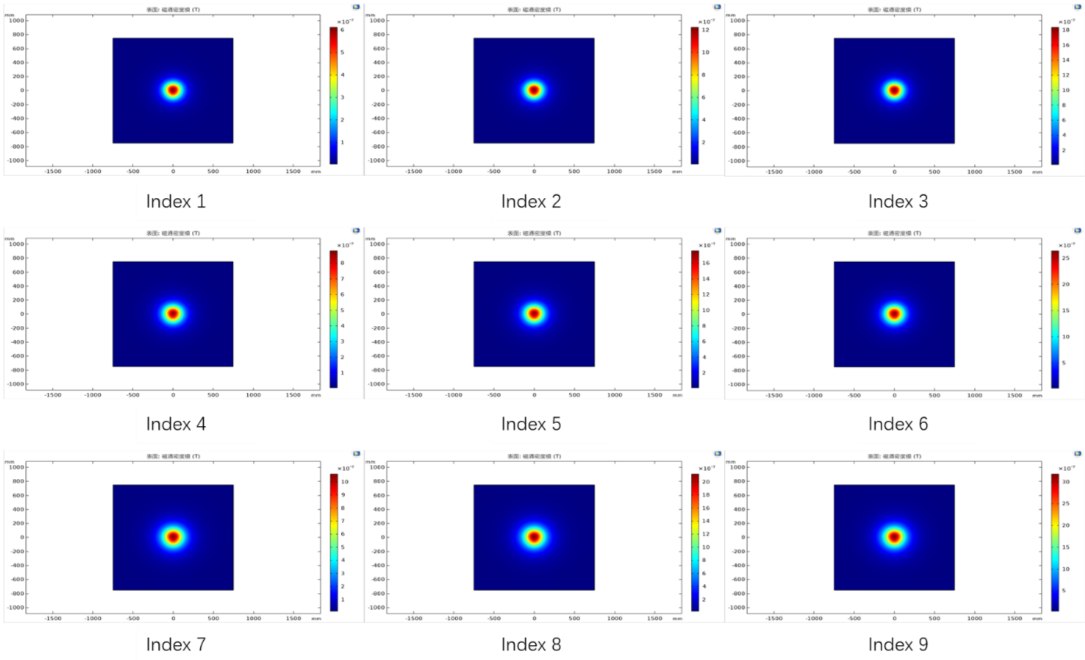

Figure 8: Distribution of magnetic field in solenoid spatial position experiment

3.2 Experiment of customized magnetic focusing generator based on patient brain data

The 3D model of the patient's tumor and skull is printed according to the established 3D files of the patient's tumor and skull, as shown in Fig. 9.

Figure 9: Patient tumor and skull generated by 3D printing

According to the experimental results of the hemispherical solenoid array, we selected the point positions of 1.2, 1.5 and 1.8, the number of windings as 40 and the current in the solenoid as 1A. Such parameter combination meet the requirement of magnetic focusing and also the magnetic energy consumption for the combination is relatively small. Then we 3D-print the patient customized magnetic focusing generator, which is as shown in Fig. 10.

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Figure 10: Patient customized magnetic focusing generator obtained by 3D printing according to the method proposed in this paper

The solenoids in the column area shown in Fig. 10 were placed to measure the magnetic field generated around the tumor area. Table 3 shows the simulation results and the actual measurement results. The overall error is 2.2%, which shows the effectiveness of the 3D printing method of the patient customized magnetic focusing generator proposed in this paper.

Table 3: Simulation results and practical measurement results of patient customized magnetic focusing generator model

Measuring point	Simulation result (μT)	Measurement (μT)						
		1	2	3	4	5	Average	Error
Center	1.70	1.7	1.69	1.76	1.75	1.76	1.732	1.92%
X+50mm	1.43	1.41	1.42	1.46	1.48	1.47	1.448	1.40%
X-50mm	1.44	1.39	1.4	1.45	1.42	1.43	1.418	1.71%
Y+50mm	1.55	1.47	1.45	1.48	1.45	1.48	1.466	5.49%
Y-50mm	1.43	1.4	1.43	1.44	1.43	1.45	1.43	0.15%
Z+50mm	4.55	4.73	4.74	4.68	4.69	4.71	4.71	3.60%
Z-50mm	0.73	0.74	0.73	0.71	0.73	0.74	0.73	1.08%

4. Conclusions

This paper presents a 3D printing method of a customized magnetic focusing generator for brain tumor magnetic therapy. Based on 3D Unet deep learning model, the tumor in the patient's MRI data is segmented and the skull is correspondingly separated using SPM12 in the MATLAB toolkit. The 3D skull and tumor files for 3D printing are generated through 3D slicer software. By designing a hemispherical solenoid array and using COMSOL Multiphysics, the optimal focusing solenoid scheme is obtained by combining simulation with actual measurement and the corresponding solenoid position and related parameters are selected. Finally, an energized solenoid with 40 windings and 1A current is selected as the basic solenoid unit. The solenoid array is formed according to the spatial structure determined by experiment and it is applied to verify with the actual data of patients. The selected scheme can achieve the focus under an acceptable consumption. The error between simulation and actual measurement is 2.2%, which verifies the effectiveness of the method proposed in this paper. The customized magnetic focusing generator established by the proposed method is expected to provide a new means for clinical treatment of brain tumors.

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