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Design and implementation of three-dimensional model for medical image of bone defect

B H Feng^{1,2}, W W Cai¹, P E Zhou¹, J X Luo^{2,3}, H F He^{2,3} and L F Peng¹

¹Guangdong pharmaceutical university, 280 Waihuan east road, Guangzhou higher education mega center, Guangzhou, P.R.China

²Guangdong province engineering and technology research center for medical 3D printer and personalized medicine, Guangzhou, P.R.China

³Soongon technology company limited, Shenzhen, P.R.China

Corresponding author: tfengbh@gdpu.edu.cn

Abstract. Bone defect caused by trauma and tumors is an important problem to be solved in orthopaedic clinic. Bone defects caused by various reasons have different shapes. In this paper a model of bone defect was created by 3D printing technology, which was tailor-made for doctors to simulate the bone defect before operation. Firstly, CT files of bone defect were imported into the Mimics medical image control system, then the pathological model was formed by image processing and three-dimensional reconstruction. Secondly, the 3-matic forward engineering software was utilized to realize the design model of bone defect repair by describing, mirror image and bone repair. Thirdly, after processing the design model with Cura chip software, the PLA macromolecule material was used to make the physical object by 3D printer. By researching the design method, forming quality, printing speed, structure and performance parameters, researchers explored the manufacturing technology of 3D printing products for bone defect.

1. Introduction

The application of three-dimensional (3D) printing in biomedical is more and more extensive, especially in the field of bone disease treatment[1]. Trauma, tumor resection, surgical revision, deformity correction and infection can all cause bone defect and then cause delayed union or nonunion of bone. So far, bone defect and nonunion are still important problems to be solved in orthopaedic clinic. At present, the methods of treating bone defect mainly include autogenous bone transplantation, allogeneic bone transplantation and artificial material filling. Autogenous bone transplantation is the most important method at present, but it may cause new bone defect trauma and cannot cope with large area defect. With the development of image processing and the maturity of 3D printing technology, the design and establishment of 3D model of bone defect image cannot only precisely individualize the treatment of bone defect patients, but also reduce other trauma or disease after treatment[2,3]. The 3D printing technology abandons the traditional factory-based production mode. It can quickly and conveniently prepare individualized implants for patients. The production cycle is significantly shortened. It breaks the time and space constraints of traditional manufacturing industry and has important social benefits. At the same time, 3D printing technology, which integrates image technology, computer-aided technology and manufacturing, can be helpful for more intuitive communication between doctors and patients. It is useful for clinicians to evaluate the conditions



comprehensively before operation, designing more reasonable operation plan. Therefore, significant clinical benefits are that operation time will be reduced to prevent intraoperative bleeding and various complications[4-8].

Based on image technology, 3D reconstruction computer-aided design technology was used to reconstruct the defect area. Individualized implants of patients were prepared by using 3D printing equipment to repair bone defects or bionic models before surgery, which could greatly improve the accuracy and safety of surgery[9]. Aim at bone defect repairing, researchers firstly obtained the CT image of the affected area and carried on the image processing to eliminate the redundant information. The processed CT images were constructed into 3D models, and then the defect parts were repaired according to the needs. The defect parts were derived and thickened. Then, they were imported into the 3D printer, the corresponding parameters were set and printed in kind. This method was suitable for designing and manufacturing the medical model of bone defect repairing with complex boundary.

2. Materials and methods

2.1 CT image preprocessing

The DICOM format files containing CT image of continuous slices were imported into Mimics 17.0 software and converted into digital images of continuous slices. Image filtering was used to highlight the parts of interests in the image, which could reduce the noise of the image and improve the image quality. The denoising filter could reduce the images noise by calculating the average value of the pixels domains and eliminating the spatial high frequency component. The CT values of skeleton, muscle and lung were distinctly different. Those tissues with large differences in the gray values could be effectively segmented by threshold segmentation and region growth. Thus the skeletal parts with large CT values were separated.

2.2 Design and Reconstruction of 3D Model Based on CT Scanning Images

2.2.1 Mirror Model and Guide Curve Creation. Firstly, we used 3-matic software to describe the missing area by mirror method. The missing area could be drawn on the constructed plane, and the 3D model was constructed according to the guide curve and the defect region on the plane. Finally, the defect region was generated and separated. This method was suitable for complex cases such as bone defect.

2.2.2 Construction of prosthesis. The curve and plane of the defect area were selected in the software. A 3D model was constructed according to the guide curves and the defect area on the plane. The model was exported to a 3D printer in STL format.

2.3 3D Printing Forming

In this research the fused deposition modelling (FDM) 3D printer M2030 of Shenzhen Soongon technology Co., Ltd. was used to form the bone defect model with polylactic acid (PLA) as material. The forming parameters including the support, base, temperature, slice thickness and so on were set in Cura software, and the solid model was printed out.

3. Results and discussions

3.1 3D reconstruction based on Mimics

Mimics were widely used in the academic and commercial fields of orthopaedics, maxillofacial surgery and cardiovascular industry. Its advantages lied in its powerful functions, high integration and easy using. Image processing mainly included Binomial blur (noise reduction filter), Curvature flow (sharp edge processing) and Discrete gaussian (Gauss filtering). Through many attempts, the appropriate number of iterations was selected to reduce the noise of CT image and make the bone

defect contour clear, so as to obtain a clear moderate contrast image. Then it was convenient to remove the redundant information in the image, and make the bone tissue distinct from other tissues, which was helpful for subsequent modeling.

Due to the use of the mean filter, the filter could remove the particle noise in the image, but it also caused the blurring phenomenon appeared in images because of the average. But it had no effect on the later modeling, because the 3D model was based on mask. The structure of the filtered mask was the same as the former one. Only the filtered noise in image was eliminated, and the filtered 3D model brought out smoother. We used "Thresholding" to select protrude points of skeletal gray scale to create "Mask" (target data point sets). The Mask generated in the previous step also contained non-skeletal parts. Using region growing method, any data points of skull were selected as seed points. According to known "Mask" and seed point, the neighboring data points sets of seed points were obtained as "Mask", which meant that the skeletal data points were segmented.

The "Calculate 3D" (3D reconstruction) was used to set the smoothing factor and iteration steps. Smoothing the 3D model was processed to obtain the required 3D pathological bone model, as shown in figure 1a.

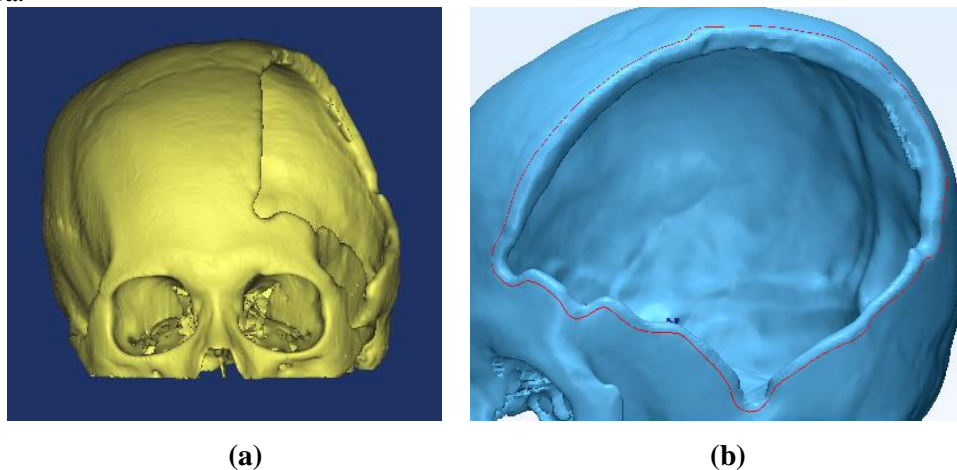


Figure 1. Reconstructed model (a), contour of defect (b).

3.2 Repair of bone defect based on 3-matic

Digital computer aided design (CAD) used a single triangle element to describe the model. Compared with traditional CAD, it used three elements to describe the model: point, line and surface. It reduced the complicated geometric relationship calculation between different elements and made the model processing faster. All operations of 3-matic were processed in digital form, which could directly reduce the repetition between reverse engineering and traditional CAD, and could be processed directly by STL format in subsequent CAD.

Pathological model pretreatment. After importing the STL format file of pathological model, the tool in "Fix" menu (repair menu) of 3-matic software was used to pretreat the model, which made the model smoother and helped to extract the contour of skull defect. "Reduce" function was used to reduce the number of triangles. The model was made by a digital CAD, so reducing the number of triangles could make the follow-up operation faster. Then the "Wrapping" and "Smoothing" functions were used to make the model smoother.

Creating the contour of the defect. We created a contour line at the defect site of pathological model by using "Create Curve" function, and then built a surface based on this contour line, as shown in figure 1b. Firstly, the model was optimized by "Wrap". "Create Curve" and "Options" were used to select "Smooth Curve", tick the parameters "Attract Curve", describe along the missing area. When the last point was near, we selected "Close Curve" command to close the curve. In order to make the curve more suitable for the missing area, we selected the "Create Curvature Analysis" command and set

"Histogram range" parameter to "-0.5" and "0.2". Then the "Edit Curve" command was selected to make the curve more suitable for the edge of the missing area.

Creating a guide line. Firstly, two anatomical punctuation points were selected in the pathological model, the sketch was positioned in the sagittal plane. The sketch was adjusted to be as even as possible. Then "Mirror" was used to create a copy of the mirror. By adjusting the position, the copy of mirror was directly within the defect, as shown in figure 2a. The contour of the defect and the anatomical structure information of the mirror model were imported into the intersection of the sketch. The guiding curve was drawn according to the skull of the mirror image on the sketch. Commands of "Create Spline" and "Select and drag" were carried out to create a wire to fit the model contour, as shown in figure 2b, according to the start and end points.

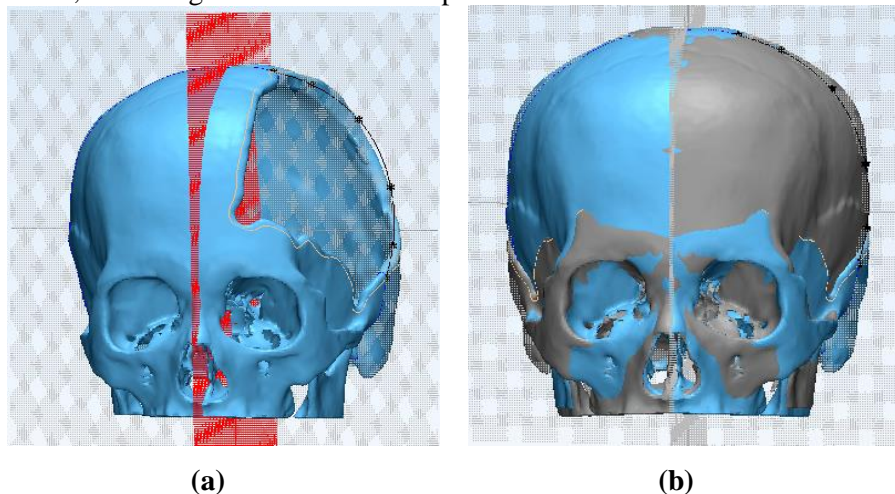


Figure 2. Adjusting the position(a), drawing the guide curve(b).

The "Create Cranioplasty Prosthesis" tool was utilized by selecting the required parameters such as the defect contour and the guide curves created after the mirror image. "Defect contour" was used to select the curve of the defect area. "Guide curves" were used to select the plane. Under the command of "Undercut Removal", the "Entity" parameter was used to choose the prosthesis model, the "Fitting entity" was applied to choose the skull pathological model, which separated the repair model from the skull pathological model shown in figure 3a. The "Smooth Edge" command was carried out after the skull cap contour that needed to be smooth was selected. "Chamfer Edge" command was chosen to make the contour of the groove smooth. Finally defect model was reconstructed as shown in figure 3b.

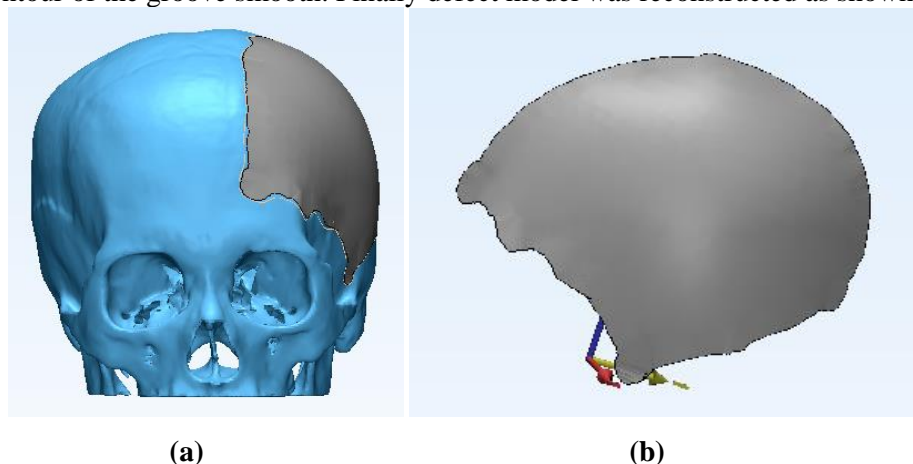


Figure 3. Pathological model with defect repair model (a), defect repair model(b).

Pathological model data and defect repair data were saved in STL format, but those data could not be directly recognized by 3D printers. Cura software was needed to convert them into "gcode" files

that could be recognized and set the parameters needed for printing. The setting of printing parameters of Cura software mainly included layer thickness, wall thickness, filling rate, printing speed, printing temperature, support and platform attachment. Pathological model and defect repair model were printed in two parts. The layer thickness parameter was set as 0.1 mm. Thickness parameters were selected according to the type of printed model. As a preoperative model of skeleton, it required high accuracy of hardness. The results of comparing different layers thicknesses were as shown in table 1. From the test data in the table, it could be seen that the faster forming speed was obtained when the thickness was set to 0.2 mm. The printing time was about half of that when the thickness of the layer was 0.1 mm for the same model. The forming speed was slow when the thickness was 0.1 mm, but the quality of the model was high, which met the requirements of the preoperative skeleton model.

Table 1. Thickness comparison.

Model	Layer Thickness (mm)	Wall Thickness (mm)	Bottom Excision	Printing time	Assessment
Pathological model	0.2	0.8	8	40hr22min	faster, poor quality
	0.1	0.8	8	80hr31min	slow, high quality
Defect model	0.2	0.8	8	3hr30min	faster, poor quality
	0.1	0.8	8	6hr42min	slow, high quality

Beside the thickness, the parameter printing speed was set to 80 mm/s. First of all, printing speed was an important parameter to determine the quality of the model. Too fast speed would reduce the quality of the model and even cause machine failure. When the printing speed was fast, it could lead to the first layer leaving the platform. At that time, the printing speed should be reduced so that consumables had enough time to bond to the platform. Second, faster printing speed meant that each layer had not enough time to cool and shape, resulting in overheating and easy deformation. When the object was overheated and the melted consumables were extruded from the nozzle, the temperature was between 190 and 240 degrees. At those temperatures, the plastic was very easy to deform. Only when the extrusion temperature and heat dissipation were in a relatively balanced position, the plastic could flow out of the nozzle and quickly cool to form. Thirdly, too fast printing speed could also lead to layer migration. The printer used in the research was an open-loop system. A stepper motor drove the machine movement. The printer could not detect the position of the printer head. When the printer head was disturbed by external forces or greater resistance, it might lead to the misalignment of the printer head, which had no detection and correction measures. So it was important to keep the printing speed under the speed that stepper motor could handle.

Another important parameter of FDM printer was the nozzle temperature. The nozzle temperature was determined by the material. The consumptive material used in this study was PLA, its corresponding nozzle temperature was usually set to 190 - 210 degrees. If the temperature of the nozzle was too high, it might lead to residual objects which was considered as wire drawing. Because when the extrusion head temperature was too high, the consumables in the nozzle would become very sticky and easy to flow out from the nozzle. But if the temperature was too low, the consumables would be more difficult to extrude. In addition, too high printing temperature might also lead to untimely heat dissipation, so that the object was overheated and the model was deformed. Low nozzle temperature would lead to wire biting phenomenon, that was, the extruder wheel bitted off a piece of consumables. The consumables did not move, but the extruder wheel had been rotating. Plastic debris appeared near the extruder. So the temperature should be raised appropriately.

Consumables flow was also known as extrusion volume, which directly determined the quality of printing. The insufficient extrusion volume would lead to the problem of weak filling. Filling was a very important part of a printed object. It undertook the function of supporting and connecting the edges of the printed parts. If a weak filling appeared, the object would be very vulnerable to damage.

3.3 3D Printing Forming

It was important to have a horizontal printing bed. Too close contact between the nozzle position and the printing bed would block the nozzle and scratch the printing bed. Far contact would cause the printing wire not to stick to the printing bed. So the distance between the printer head and the bed should be carefully observed before printing the first layer, then the screw under the printer bed was adjusted properly to ensure that distance was in a relatively suitable position. A sheet of A4 paper could be put on the printing bed. When the printing head touched A4 paper, it was the appropriate distance. In addition, it could be judged by observation whether the distance was suitable. If excess residues were observed between the middle and the outside of the printed fibres during the printing process, it was indicated that the distance between the printing head and bed was too close, the distance needs to be adjusted. If the fibres broke away from the printing bed, it needed to be closer to each other.

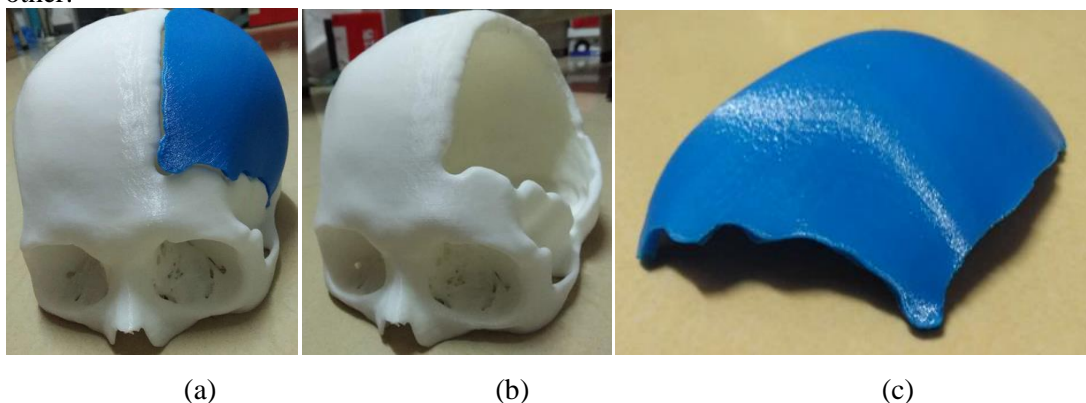


Figure 4. Combined models anterior view (a), skull pathological model (b) and defect model entity (c)

The forming temperature, printing speed and stability parameters suitable for printing model were obtained through repeated experiments. Finally the defect repair model and bone defect model were printed, as shown in figure 4a,b,c. The model had smooth appearance, high quality, strong hardness and high similarity. The reconstructed defect repair model could be well adapted to the pathological model and effectively applied to preoperative simulation, which achieved the desired results.

4. Conclusion

In the image reconstruction model, it was difficult to find the sagittal plane for image reconstruction because the original CT scanning data was misalignment. In addition, the method used to reconstruct the repair model overcame the problem of selecting five thickness points on the pathological model. There were large errors in reconstructing the repair model according to these five points. 3D point cloud data processing was often used in 3D reconstruction. Surface construction was carried out by using reverse engineering technology, so that a repaired 3D model could be obtained. However, when repairing the defect of specific patients, it was found that point cloud data processing needed to deal with a large amount of data. For skeletons with large amount of data, the processing time was too long and relatively complex. Therefore, according to different situations, we chose the method to design the 3D model.

In this study, 3D printing technology for skull defect repair was mainly studied. The model could also be applied to clinical preoperative planning and simulation under the condition of ensuring printing accuracy and hardness. The full scaled 3D printed bone model could be helpful for clinicians to plan and simulate the operation in detail, such as choosing the kind of steel plates, shaping the steel plate safely, placing the steel plate, and placing the screw. All the difficulties that would be encountered in the operation could be rehearsed in advance. A perfect preoperative plan could be obtained. It would make the operation more accurate, safer, more efficient and faster, reducing the amount of bleeding during operation. Therefore, 3D printing technology was worthy of wide application in orthopaedic clinic, even in the whole medical industry.

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