The use of CT scan and stereo lithography apparatus technologies in a canine individualized rib prosthesis

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Abstract

Objective: To design and fabricate canine rib prosthesis with full geometric shape using computed tomography (CT) scan combined with computer-aided design (CAD) and stereo lithographic (SLA) technologies and to evaluate the accuracy of this method.

Methods: After scanned on 64 rows helical CT, the cortex part of the right 7th rib was selected as the prototype for design and manufacture of the rib prosthesis and image data were stored as DICOM format. Three-dimensional (3D) surface reconstruction was applied to produce 3D image of the 7th rib and results were outputted as STL format which were then modified by UG software for establishment of CAD model.

Results: The rib prosthesis with full geometric shape was obtained based on CT scanning and SLA technique. About 30,000 point cloud data were acquired after 3D laser scan of the ribs. When comparing the rib prosthesis with the rib prototype, the maximum positive deviation, maximum negative deviation, average deviation and standard deviation were 1.764 mm, 2.126 mm, 0.183 mm, 0.253 mm and 0.346 mm, respectively. There were about 88.17% of the point cloud data within the range of ±0.5 mm.

Conclusion: It is feasible to design and fabricate rib prosthesis with full geometric shape by using CT scanning technology combined with CAD and SLA technologies. This method is fast, convenient and precise for manufacturing prosthesis. Optimization and improvement could be processed based on the deviation suggested by the scanning.

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1. Introduction

The rib cage comprises the sternum, ribs, interconnecting joints, and soft tissue. The geometric shape of ribs contributes not only to the thoracic appearance but also to the biomechanical property. Some factors including age, mineral density, spinal disease and thoracic deformity all can affect the rib structure and shape that change the normal biomechanics properties of it, and then result in its function damage. Chest tumor, infection, trauma and other reasons may lead to rib damage or resection, which can cause chest wall defect or softening. Clinical studies show that the structure defect of ribs leads to the lacking of effective support to the chest wall, the obvious appearance change of thorax, and the reduction of chest wall compliance, thus affects the breathing and movement function. Fortunately, reconstruction of chest wall with artificial ribs plays a vital role. Thomas et al. believe that during the reconstruction of chest wall, it is necessary to maintain a good thoracic appearance in addition to assure the thoracic stability and airtightness. To avoid the significant changes of chest cage after thoracoplasty, the great importance is to create artificial rib (prosthesis) which has the physiological geometric shape and certain mechanical properties. However, the existing reconstruction materials cannot satisfy the requirement of unique complex solid geometry shape for the ribs except that they can meet to the requirements of mechanical strength, histocompatibility and biological safety.

In recent years, with the development of computer-aided design/computer-aided manufacturing (CAD/CAM) and digital image technology, as well as the combined application of them in the field of medicine, individual artificial prosthesis, anatomy/disease model, tissue engineering scaffolds and so on have been successfully applied to reconstruct and restore the defect organization in
craniocerebral surgery, orthopedics, plastic surgery and other subject areas.  

Rapid prototyping technology with characteristics of rapidity, advancement and accuracy has been successfully used to manufacture artificial prostheses and anatomical models. In this study, we attempted to manufacture rib prostheses with full geometry shape based on digital scanning combined with CAD technology and rapid prototyping manufacturing technology and meanwhile evaluate its accuracy by comparing to the real prototype.

2. Materials and methods

2.1. Experimental animal preparation and processing

Healthy male mongrel dogs (2 years old, weighting around 18 kg) were used in this study. They were fed according to Animal Breeding and Use Ordinance (1996 edition), and the animal experiment procedure was approved by the Animal breeding and use management committee, Tong Ji hospital affiliated to Tong Ji University. After sedated by intravenous ketamine (10 mg/kg), the experimental canine was subject to chest computed tomography (CT) scanning. The animal was euthanized by furane suction and intravenous injection of pentobarbital sodium (200 mg/kg). After anatomization, the cortex part of the right 7th rib was collected as the prototype for design and manufacture of artificial rib.

2.2. Rib image data collection and format conversion

The rib was scanned on 64 rows helical CT (Lightspeed VCT, GE Healthcare, USA) with both layer spacing and thickness of 0.625 mm. The images were stored in the computer as the format of DICOM. The new DICOM image was obtained by using multi-planar reconstruction based on the stratification of rib images according to its long axis direction. Through region of interest (ROI) based analysis of imaging data, the cortex part of the right 7th rib was selected as a prototype. Then function of threshold segmentation and regional growth were applied to remove the soft tissue and finally the 7th rib segmentation image was obtained. The 3D image of the 7th rib was produced by three-dimensional (3D) surface reconstruction, and the result was outputted as STL files.

2.3. Rib entity manufacturing

Unigraphics NX (UG) software (Siemens PLM software, USA) was used to process the output STL files. The interference and redundant data were deleted and the missing data was repaired. Then the digital data was subject to smoothing, noise reducing and relaxation processing to restore the dog 7th rib anatomic structure and geometric shape as good as possible.

Thus the rib entity model (CAD model) was established, and the data was inputted into the stereo lithograph apparatus (SLA) rapid prototyping machine (SPS600B, Shaanxi Hengtong Intelligent Machine Co., Ltd, China) as the IGS format files following the process of stratification, adding support, generating tool path and so on. The right 7th rib was manufactured with 14120 photosensitive resins (Somos, USA) as the materials. The thickness of each layer was 0.1 mm and the precision was ±0.1 mm.

2.4. Evaluation the accuracy

Three-dimensional scanning system comprised flexible arm (CimCore, USA) and 3D laser scanning system (Perceptron, USA), which was applied to scan the artificial rib entity and the rib prototype. The point cloud data was obtained and preserved as STL file format. Rib prototype was treated as a reference template while artificial rib entity was treated as test object. Best fit method based on Geomagc Qualify software (Geomagic, USA) was used to compare the rib entity and the prototype under a common coordinate and the chromatogram was generated automatically. Colors represented the difference degree between them and deeper color meant larger difference. The range was set as ±0.5 mm. Deep red represented +0.5 mm. Dark blue represented −0.5 mm.

3. Results

3.1. Artificial rib manufacturing

By application of CT scanning combining with CAD/CAM and SLA techniques, we could manufacture rib entity with similar outline and geometry shape to real rib (Figs. 1 and 2).

3.2. Evaluation the accuracy of rib entity

About 30,000 point cloud data were generated after laser scanning. The data were inputted into the Geomagic Qualify software, and the Best fit method was applied for matching comparison (Fig. 3). The three-dimensional chromatogram showed that most colors were between red and blue, which indicated that the majority of errors for rib entity were within 0.5 mm (Fig. 4).

Based on the analysis of the Geomagic Qualify, we found that the maximum positive deviation, maximum negative deviation, average deviation and standard deviation was 1.764 mm, −2.126 mm, 0.183 mm, −0.253 mm and 0.346 mm, respectively. The percentage of point cloud data was 4.183%, 11.335%, 15.888%, 18.228%, 16.244%, and 8.618% at the percentage deviation of 1.0, 1.1, 1.2, 1.3, 1.4, and 1.5, respectively. The percentage of point cloud data was 2.385%, 8.925%, 60.5% and 19.594% at the standard deviation of 2.0, 1.1, 1.0 and 1.0, respectively. There was 3.589% of the point cloud data were beyond the positive deviation value we set, while 8.249% beyond negative deviation value, thus a total of 11.83% of the point cloud data were beyond the positive and negative deviation value we set. That is to say the vast...
majority of point cloud data (88.17%) were within the range we set (Fig. 5).

4. Discussion

To our knowledge, this is the first report about the application of digital scanning technology, combined with CAD and SLA technologies to design and fabricate rib prosthesis with full geometric shape. Due to the relatively complex surface of the ribs, their geometric shapes are various from each other, which bring great challenge to create accurate artificial rib prosthesis. However, the traditional industrial molding technology, such as car, planning, casting, stamping and so on, usually use the standard anatomical structure of the object to process and manufacture, thus they can't satisfy the needs of clinical “individualization” treatment. What's more, traditional methods have complicated procedures that need to finish drawing, process design, mold tooling manufacture and others. Meanwhile, in clinical practice, it is impossible to provide the prototype (rib) for processing and manufacturing. Application CT or Magnetic Resonance Imaging (MRI) scans to get the digital information of bones or organs for the manufacture needs, combined with CAD and SLA technologies to manufacture medical prosthesis, mold or anatomical model, is a relatively mature technology.\(^{13-16}\) CT or MRI scan can quickly capture the geometric characteristics and all the geometric data is saved in the form of digital format, which can be easily manipulated during the design and modification process. In addition, the images data can be quickly converted to STL format for fabricating rapid prototyping. Therefore, digital information can be stored and to be used for personnel identification. In the current study, we created a rib entity with full geometric shape, the size and form of which were completely consistent with that of prototype. This prosthesis intuitively and accurately showed the anatomical shape structure of the rib. Therefore the technology method is feasible for manufacturing rib prosthesis with certain geometric shape. Besides, this method is convenient and rapid.

The accuracy was evaluated by employing Geomagic Qualify software, which is reverse check software, with straightforward graphics to display the difference between two ones. Through a random point measurement and analysis, we established deviation profile. In close to 30,000 point cloud data between entity and prototype rib, we found that 69.44% of the point cloud data were ranged in $\pm 1$ SD and 91.42% of point cloud data were in $\pm 2$ SD. It is indicated that there is a high similarity of the geometric shape of rib entity to that of prototype.

However, there was still 3.589% of the point cloud data exceeding the positive deviation value, and 8.249% exceeding the negative deviation value. By the Geomagic Qualify software analysis, we could find that, there was greater degree of error at the costo-vertebral joints and the broken end of rib - cartilage (in both Fig. 2. Rib prosthesis (up) and rib prototype (down).

Fig. 2. Rib prosthesis (up) and rib prototype (down).

Fig. 3. Rib prototype (A), rib prosthesis (B) and best fit (C) based on scanning.

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Fig. 4. Three-dimensional chromatographic analysis of rib prosthesis and rib prototype.

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inappropriate parameter settings, may also lead to generation of errors. Because the accuracy of the rapid molding machine is much higher than the resolution of the existing CT scanning, they cannot accurately match with each other. This also is one of the reasons that the actual accuracy of manufacturing rib entity is far lower than the theoretical accuracy. Therefore, we should take thinner CT layer thickness and layer distance as possible as we can to obtain the more tiny anatomical structure. Also, we need more elaborate operation in the extraction and reconstruction of rib image, trying to avoid the loss of information and the acquisition of false shadow or soft tissue shadow. Meanwhile during the data processing based on UG software, the technical operator should know the normal structure of rib very well to avoid missing or adding of anatomical information.

Although we obtained the rib entity with full geometric shape and high accuracy based on digital scanning technology, combined with CAD and SLA technologies. At present, the artificial rib entity fabricated by CT scan and SLA method is not able in clinical application directly (that is main reason that this study says “rib entity” rather than “rib prosthesis”). The main problem is the material itself and the harmful substance generated in the forming process. Besides, the mechanical properties are limited, and the entity is not easy to disinfection. But it is feasible to fabricate artificial rib using metal or other materials according to this rib entity.

SLA technology is able to manufacture the individual prosthesis rapidly, conveniently and accurately. In this study we successfully fabricate artificial rib entity with full geometric shape and high accuracy by employing this technology. However, more researches are needed to allow the application of this artificial rib in clinic.

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Author contribution
Design the experiments: Pan Yu-qin, Ruan Zheng.
Do and interpret the experiments: Pan Yu-qin, Wang Jing, Chen Yong, Wu Bing.
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Conflict of interest
All authors have no conflict of interest to declare.

References
