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3D プリンタによる患者固有な模型作成とそれに基づく子宮筋腫の摘出手術計画への応用

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あらまし　３次元臓器模型は従来の医用画像の観察より人間の視覚と触覚において優れているため，医療現場で患者の解剖構造の理解へ活用が期待されている．３D プリンタ技術の発展によって，高精度かつ低コストで臓器模型を作成することが可能となってきた．特に，対象患者の臓器形状を忠実に再現して，外部から内部構造を観察できる透明，かつ人体組織と同程度の柔らかさを持つ臓器模型が手術計画やシミュレーションへの応用に期待さる．本研究では，MR 画像に基づく患者固有な子宮模型の作成法を検討し，作成された模型を子宮筋腫の切除手術の計画に応用する．提案法では，３D プリンタと従来の鋳型造形法を併用して，透明かつ柔軟な子宮模型を低コストで作成することができる．提案法を用いて４名の子宮手術の対象者の模型を作成し，模型の精度評価を定量的に行った．従来の画像観察法と比較して，臓器模型の有用性が示された．

キーワード　子宮筋腫，MR 画像，３次元人体模型，3D プリンタ，鋳型技術

Patient-specific model generation by using 3D printing and its application to surgical planning of uterine fibroid removal

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Abstract: 3D physical models of inner organs have been expected for a quick understanding of a patient anatomy due to the better reality, portability, and tactile impression compared to conventional 2D/3D medical image visualizations on a computer screen. 3D printing provides a possibility to generate an accurate 3D physical model conveniently with low cost. Especially, a patient-specific model with transparent and elastic materials is expected as an essential tool for supporting surgery planning and simulation. Our study proposes an approach to generate such a physical model with low cost for supporting uterine surgical operations based on MR images by using a hybrid technique (inexpensive 3D printer and mold casting). We applied this method to generate uterine models for four patients before the surgical operations and evaluated accuracy of the models quantitatively. Compared to the conventional method based on image observations on a screen, the advantage of the 3D physical model for surgical planning was demonstrated.

Keywords: Uterine fibroids, MR images, 3D physical model, 3D printer, Mold casting.

1. Introduction

The uterine fibroids are very common non-cancerous (benign) growths that develop in the muscular wall of the uterus and the primary cause of morbidity in women at reproductive age. The conformation of size, type, a location of uterine fibroids under patient-specific anatomical structures is required for treatments [1, 2]. The conventional method for the conformation is to interpret the many 2D MR images on a computer screen, which is time-consuming and requires experience. A patient-specific physical model, which represents the target organ with its complex internal structures, is more intuitive for a quick conformation of the anatomical structures. Recently, 3D printing technology provides a possibility to generate such a physical model quickly and accurately to show complex internal structures with a higher versatility and fewer space requirements [3, 4].

The purpose of this work was to propose a method to create a uterine 3D elastic model with transparency. Our method uses a hybrid technique by combining the conventional 3D printing and traditional mold casting to generate a high-reality and low-cost physical model required by surgeons. We applied this method to create uterine models for supporting real surgical operations and evaluated the accuracy and usefulness of the generated models.

2. Materials

The MR images (T2-weighted) of twelve women cases were used in this study. Each image showed information of the uterine region in a spatial resolution of 512 x 512 pixels, field-of-view of 30 x 30 cm^2, and with section thickness/gap of 2 mm. Two patient cases (one simple case and one complicated case) with uterine fibroids and two patient cases for uterine removal operations were selected as the examples of 3D physical model generations.

3. Methods

The process of creating a uterine 3D physical model includes three steps: image processing, model creating, and model validation as shown in **Fig. 1**. The details of each step are described in following sections.

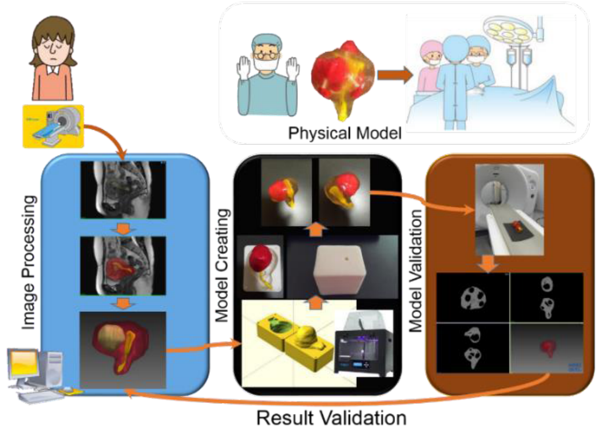


Fig. 1 Overview of 3D physical model generation to support surgical planning for removing uterine fibroids based on MR images

3.1. Image Segmentation

In all MR image datasets, the anatomical uterine structure (uterus body, endometrium, fibroid and blood vessel) is segmented using a semi-automatic approach and visualized in 3D by using surface rendering based on the Medical Imaging & Interaction Toolkit (MITK) open-source framework [1, 5]. The final output of smooth surface rendering is automatically converted into standard tessellation language (STL) format. The STL file is sent for mesh processing such as cleaning, smoothing, surface reconstruction and texturing, and meticulous filling.

3.2. Model Creation: 3D-Printing, Molding and Casting

We divide the final version STL into several parts; uterine body mold, internal components model (endometrium with fibroid) and blood vessel, and generate the STL file for each part respectively for 3D printing. 3D printer used in this research is a fused deposition modeling (FDM) type, inexpensive, easy to handle and maintain [3, 4]. The printing material is poly-lactic acid (PLA) filament.

The generation of the 3D physical model of the uterine body is based on traditional mold and casting technique. We manually paint the colors on endometrium (yellow), fibroid (red) and blood vessel (yellow-red), and then attach all parts (endometrium, fibroids and uterus body mold) together, inject the gel into the seal mold and wait for several hours or days (depending on material). Finally, we pull apart the shell carefully and finish the 3D physical model generations.

3.3. Model and Result Validation

In order to validate the generated models, we scan the final products of the 3D physical models by using a CT scanner. We compare the CT images that show the essential information with the MR images, on which the patient anatomy is recorded. We also evaluate time and cost, as well as the accuracy of the 3D physical models, by comparing the original patient (MR images) with the 3D physical model (CT images). Then we evaluate the accuracy of the uterine body based on MR images before the operation, 3D physical models (CT images) and patient resected organ or specimen samples (CT images) for two selected uterine removal operation cases.

We evaluate the time and cost by using two kinds of materials; gelatin and polyol with isocyanate for creating the 3D physical models. To assess the accuracy of our model, we use image-based evaluation by scanning the 3D physical models and resected uterine organs of CT images and compare it with the original patients' MR images. We measure the STL uterine body volumes and distances between two sets of landmarks on the surfaces using registration [5, 6] between original uterine MR images and 3D physical model CT images for simple and complicated cases and two selected uterine removal operation cases.

4. Results

The 3D physical models that we cast using gelatin and polyol with isocyanate are shown in **Fig. 2**. The total process time and cost for 3D physical model of the simple case using gelatin and polyol with isocyanate are about ± 30 hours, ± 1,200 Yen and ± 35 hours, ± 6,000 Yen, respectively. While the total process time and cost for 3D physical model of the complicated case using gelatin and polyol with isocyanate are about ± 40 hours, ± 2,000 Yen, and ± 45 hours, ± 8,500 Yen, respectively.

The measurement result of the uterine body STL volume difference for each material was about ≤ 32.8 cm^3, and the result of measuring the average distance between the two sets of landmarks (original uterine MRI vs. 3D model CT images) on the surface showed that the gap is less for gelatin which was 0.16 mm (4.64 pixels) compared to polyol with isocyanate which was 0.28 mm (8.37 pixels). The gap difference between the two materials is 0.20 mm (5.89 pixels). Each material showed almost the same gap distance compared to the original uterine MRI, averaging ± 0.14 mm (4.10 pixels) for the complicated case. The difference of gap between the two materials was small and about 0.09 mm (2.67 pixels).

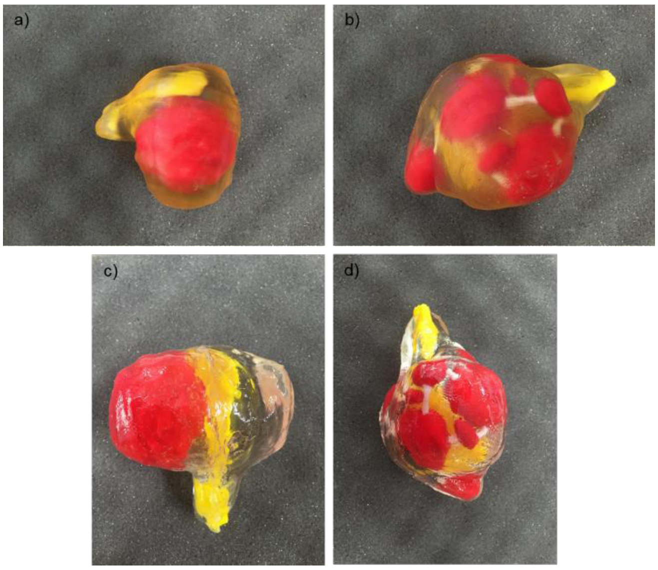
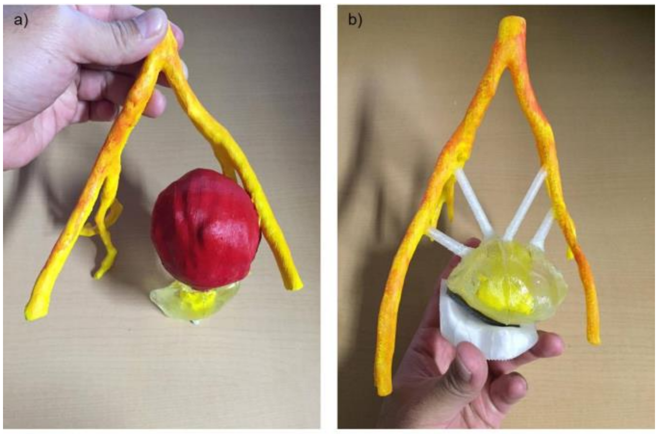


Fig. 2 3D physical models for two patients. a) A simple case using gelatin, b) a complicated case using gelatin, c) the simple case using polyol with isocyanate, and d) the complicated case using polyol with isocyanate.

The results of the 3D physical model for two selected uterine removal operation cases are shown in **Fig. 3**. The volume difference for each STL uterine body volume is about ≤ 24.6 cm^3, and average distances between the two sets of landmarks on the surface for the case on 27 Nov 2015 showed a slight gap between each set, with an average of ± 0.11 mm (3.34 pixels). Patient case on 6 Dec 2015 demonstrated that the difference gap between sets larger for patient resected organ versus (vs.) 3D physical model (0.15 mm (4.48 pixels)) and smaller gap between original uterine MR images vs. 3D physical model (0.10 mm (2.91 pixels)). Our experimental result shows that there is a slight difference between our 3D physical models and original uterine (MRI and CT images).



(a) 27 November 2015 (a) 6 December 2015

Fig. 3 3D physical models for two cases using polyol with isocyanate; uterus (transparent), endometrium (light yellow), artificial connection and bladder (white), vessel (yellow)

5. Discussion

In our study for 3D model generation, we focused on creating and developing order-made and patient-specific 3D physical model of uterine fibroid. Our 3D physical model was elastic (polyol with isocyanate) by using the material which is similar to human tissues and transparent for a quick examination on the endometrium and fibroid inside the uterine. The low cost of 3D physical model (<10,000 Japanese Yen) makes it possible to be frequently and widely used for surgical planning.

We successfully analyzed the accuracy and usefulness of uterine fibroid removal using a combination of the computer-based visualization and patient-specific 3D physical model by comparing with the patient original uterine fibroid MRI and patient resected organ (CT images). The accuracy in measuring the gap between each subject 3D physical models, original patient MRI and patient resected organ (CT images) showed a slight difference between each subject. We can conclude that our 3D physical models are very reliable as they are similar to the original uterine. The uterine 3D physical models also can be clearly visualized, touched and it is possible for hands-on practice. This will help surgeons in explaining to patients on the required treatments and procedures for the surgery.

6. Conclusion

Preliminary results demonstrated potential accuracy and usefulness for surgery support. Generating uterine fibroid patient-specific models with 3D printing technology is practical with refinement in certain aspects to be accomplished. The models were actually used by a surgeon, and our validation results showed the high accuracy of the models with a very slight gap between the actual patient MRI and patient resected organ. The combination of the advanced 3D printing technologies, traditional mold and casting technique with the medical imaging can be a useful tool for communicating with patients and surgery planning support for uterine fibroid removal.

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