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Evaluation of pre-surgical models for uterine surgery by use of three-dimensional printing and mold casting

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Abstract We propose an approach to supporting pre-surgical planning for the uterus by integrating medical image analysis and physical model generation based on 3D printing. With our method, we first segment the patient-specific anatomy and lesions of the uterus on MR images; then, we create a 3D physical model, an exact replica of the patient's uterus in terms of size and softness, with transparency for easy observation of the internal structures of the uterus. In our experiments, we created pre-surgical models of hysterectomy for five patients who had been diagnosed to have uterine endometrial cancer. An experienced radiologist, the surgeons, and all of the patients cooperated in our experiment for carrying out subjective evaluations of the usefulness of our model. The accuracy of the physical models was evaluated quantitatively by comparison between the MR images of the patients and the CT images of the models. The results showed that the mean values of the errors in gap ranged from 1.19 to 2.22 mm, which was satisfactory for the surgeons. The feedback from both surgeons and patients demonstrated the usefulness and convenience of the models for efficient patient explanation understanding and pre-surgical planning by surgeons.

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1 Introduction

Uterine tumors such as fibroids and cancers are common lesions in women, and surgical procedures are one of the treatment options. The surgical treatment for uterine fibroids or cancers always requires information about the patient's uterine anatomy and tumor location, and medical images are the only means for providing such information. A typical image modality for uterine diagnosis and treatment is magnetic resonance (MR) imaging, which demonstrates three-dimensional (3D) information on the internal structure of the human body by generating a series of two-dimensional (2D) image slices. A way of obtaining useful information from MR images is to interpret the 2D image slices directly on a computer screen and to predict 3D anatomic structures with lesion locations based on the surgeons' knowledge and experience [1]. However, the interpretation of a large number of 2D slices (fragments of the global human anatomy) and prediction of complicated 3D structures are time-consuming and subjective. Therefore, computer-based 3D visualization and quantitative imaging are expected to serve as complementary tools to improve the efficiency and accuracy of MR image interpretations.

Both 3D visualization and quantitative imaging are based on the results of medical image analyses, including recognition, segmentation, and measurement of the anatomic structures and lesions on medical images [2]. In our previous work [3], we developed a computer system that supports uterine surgical planning. This system selectively extracts uterine structures and fibroids, and provides 3D visualization on pelvic MR images according to the surgeons' demands. The results of our investigation showed that the time for MR image interpretation by surgeons was reduced significantly when they used our system. The efficiency and correctness of surgical planning were also improved, especially for patients who have a number of small uterine fibroids. These experimental results demonstrated that computer-based medical image analysis and 3D visualizations are useful for supporting uterine surgery planning.

The present work aims further to improve surgeons' efficiency in obtaining and using the information from MR images for surgical planning. We intend to address two issues raised in our previous work: (1) computer-based 3D image visualization lacked a feeling for actual size or distance between target organs, which is critical for surgeons; (2) the inconvenience of image visualization that depended on a computer and monitor, which are not always available in operating rooms, and whose mobility is limited during operations. Our solution is to use modern 3D printing with the traditional mold casting to generate an exact replica (a 3D physical model) which shows patient-specific structures (both rigid and elastic), together with transparency for easy observation of internal structures [4]. The paper is organized as follows: First, we give an overview of our model generation pipeline, and then, we describe the details of medical image analysis and model generation in Sect. 2. The experimental settings that include the patient cases, image protocols, and materials for model generation are described in Sect. 3, with the results including the models generated as well as feedback from surgeons and patients. The discussion is given in Sect. 4. Section 5 presents our conclusion.

2 Methods

An overview of our system is shown in Fig. 1. The process for creating a uterine model includes two parts: (1) recognition and segmentation of patient-specific anatomy on MR images, and (2) physical model creation via 3D printing with mold casting. The details for each processing step were presented in our previous paper [3]. Here, we give a brief description to introduce these functions.

The first step for model generation is to obtain information about the patient's anatomy and lesion location. In the case of the uterus, this includes the body of the uterus, the endometrium, any endometrial cancer, and the blood vessels, as required by the surgeons. The MR images serve as a resource. We developed a system for segmenting these structures on MR images using a semi-automatic algorithm, and we provided a 3D visualization interface based on a surface rendering technique for validating the results [5, 6]. The user manually indicates a number of seed points on MR images, and the computer provides the contour of the target regions. This process is repeated until the result verified via 3D visualization is satisfactory for an experienced radiologist.

The second step is to create a patient-specific physical model based on the information obtained from MR images in the previous step. For accomplishing this task, 3D printing and mold casting are used. We decompose a model into a number of components and assign these components to two groups: (1) those that need accurately to preserve the shape of the uterine surface, volume size, and distance gaps between the uterine structures and blood vessels. We create the components directly by 3D printing. (2) Those that need high transparency for viewing of the internal structures and have elasticity similar to that of human tissue. We first generate molds for these components, assemble all of the components for casting, and finally create an elastic model with high transparency [7].

3 Experiments and results

3.1 Materials

3.1.1 Subjects and acquisition conditions

Five patients (mean age 50 years; age range 38–57 years) with histologically proved uterine endometrial cancer (endometrioid adenocarcinoma) were included in the study. All patients were examined with use of a 3-T MR imaging system (Ingenia 3.0T CX; Philips Medical Systems, Best, The Netherlands). A phase-array body coil was used for obtaining complete coverage of the pelvic. All patients underwent a 3D volume isotropic turbo spin-echo acquisition (VISTA) sequence. 3D VISTA (T2-weighted fast spin-echo imaging; TR/TE: 2,500/200 ms; matrix size: 512×512 pixels; field of view: 32×32 cm^2, and section thickness/gap: 1.5/0 mm) images were obtained in sagittal planes. It takes 5 min and 40 s (340 s) imaging time for one MRI 3D VISTA procedure. Contrast-enhanced MR angiography (gradient-echo imaging; TR/TE: 4.6/1.6 ms; matrix size: 512×512 pixels; field of view: 36×36 cm^2, and section thickness/gap: 1.5/0 mm) images were obtained by use of the bolus tracking technique.

3.1.2 Printing materials

Two 3D printers, named FlashForge Creator Pro Dual Extrusion and FlashForge Guider (Flashforge 3D Technology Co., Ltd., Zhejiang, China), were used in this study. Our 3D printer was an FDM (fused deposition model) category printer. The nozzle is moved in the *x*–*y*–

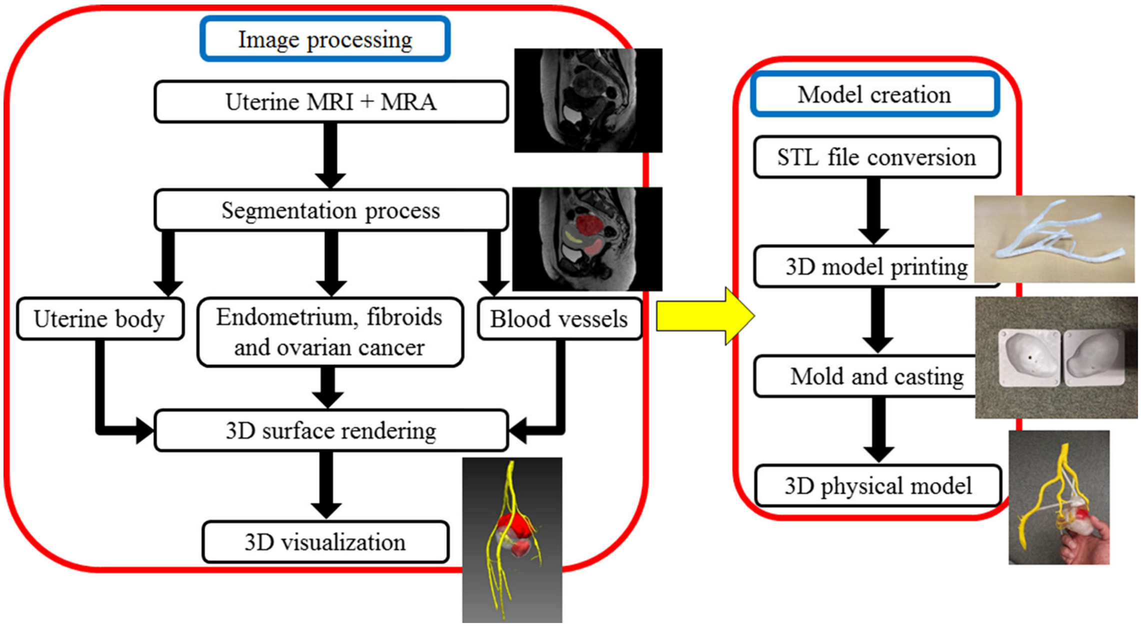


Fig. 1 Processing flow for creation of uterine 3D physical model

z directions, and the build platform can also be moved in the z direction. It is not possible to do a rotation. As printing material, we primarily used a poly lactic acid with a 1.75-mm-filament diameter biodegradable thermoplastic derived from a plant. It is safe, has consistently lesser warps, contains lesser split layers when printing is done more rapidly, and requires no heated build plate. As the material for mold casting that aims to create a realistic, transparent, and deformable uterine 3D physical model, we use polymeric materials (known as polyurethanes, from a family of polymers resulting from the reaction between an isocyanate and a polyol), which are transparent and flexible and have long-lasting durability for casting. Based on the manufacturer's specifications, the gel can last for up to 3 years under room temperature condition.

3.2 Model validations

Five patients (all of whom underwent hysterectomy) and three surgeons with experience of 21, 15, and 10 years, respectively, participated in a survey. The survey consisted of a five-point rating scale (1 = poor, 2 = average, 3 = good, 4 = very good, and 5 = excellent). Questionnaires were prepared for the surgeons and the patients, so that comparisons could be made between 2D MR images and personalized uterine 3D physical models. In the questionnaires for patients, six questions after the surgeons' explanation based on 2D MR images and 3D model were provided regarding their understanding of the disease (Q1 and Q2), explanations of the surgical procedure (Q3 and Q4), and explanations about risk of complications (Q5 and Q6), as well as the overall evaluation of 2D MR images and 3D models. The questionnaires for the surgeons were divided into three parts: preoperative, postoperative, and overall evaluation. Three questions included whether it was helpful to understand the uterine anatomic position (Q1), helpful in the preoperative explanation to patients (Q2), and helpful in the preoperative plan (Q3). Three postoperative questions asked whether the 3D physical model helped to provide information about the size of the tumor (Q4), the positional relationship between the uterus and the tumor (Q5), and the positional relationship between the blood vessels and the tumor (Q6). The last part of the survey was an overall comparison of 2D MR images and 3D models.

A CT scan of the personalized uterine 3D physical models was performed for an image-based evaluation of the accuracy of the 3D physical models, as shown in Fig. 2. The CT images, which showed essential information about the 3D physical models, were compared with the MR images. The mean value of the errors using point-based registration [8] (distances among the uterus body 3D model and original uterus patient MR images from a patient after image registration) was determined to assess the accuracy of the models.

3.3 Results

The personalized 3D physical models of the five cases, for which polyol with isocyanate was used, were generated successfully, as shown in Fig. 3. Our feedback for the patients' and surgeons' to determine whether personalized

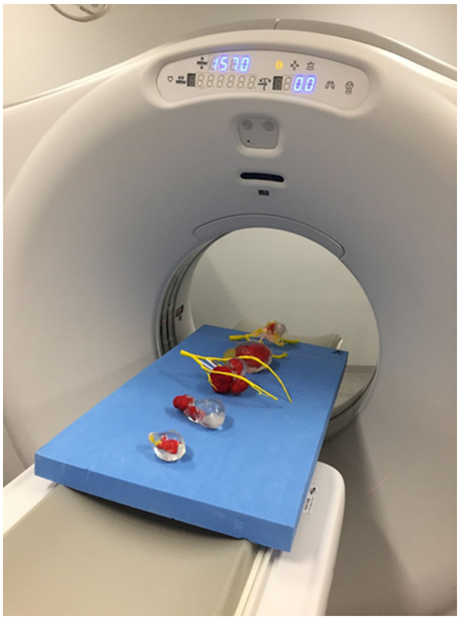


Fig. 2 CT scanning for personalized uterine 3D physical model

uterine 3D physical models might improve patients understanding of their disease, the surgical procedure and risk of complications, and the usefulness for surgical planning compared to that of 2D MR images is shown in Figs. 4 and 5, respectively. Based on the overall evaluations of the five patients who underwent uterine cancer removal, three patients thought that the personalized uterine 3D physical model was an excellent tool for the explanation by a surgeon, compared to only one for 2D MR images. Patients easily understand their disease, the surgical procedure, and the risk of complications where 3D physical models are used by surgeons, as shown in Fig. 4. In the evaluation by surgeons, out of five feedbacks, only one excellent rating was given for personalized uterine 3D physical models, compared to two for 2D MR images. The result in Fig. 5 shows that surgeons were satisfied only for facilitating the preoperative explanation to patients (Q2).

The mean value of the errors (distances between the uterine 3D physical model and the original MR images of a

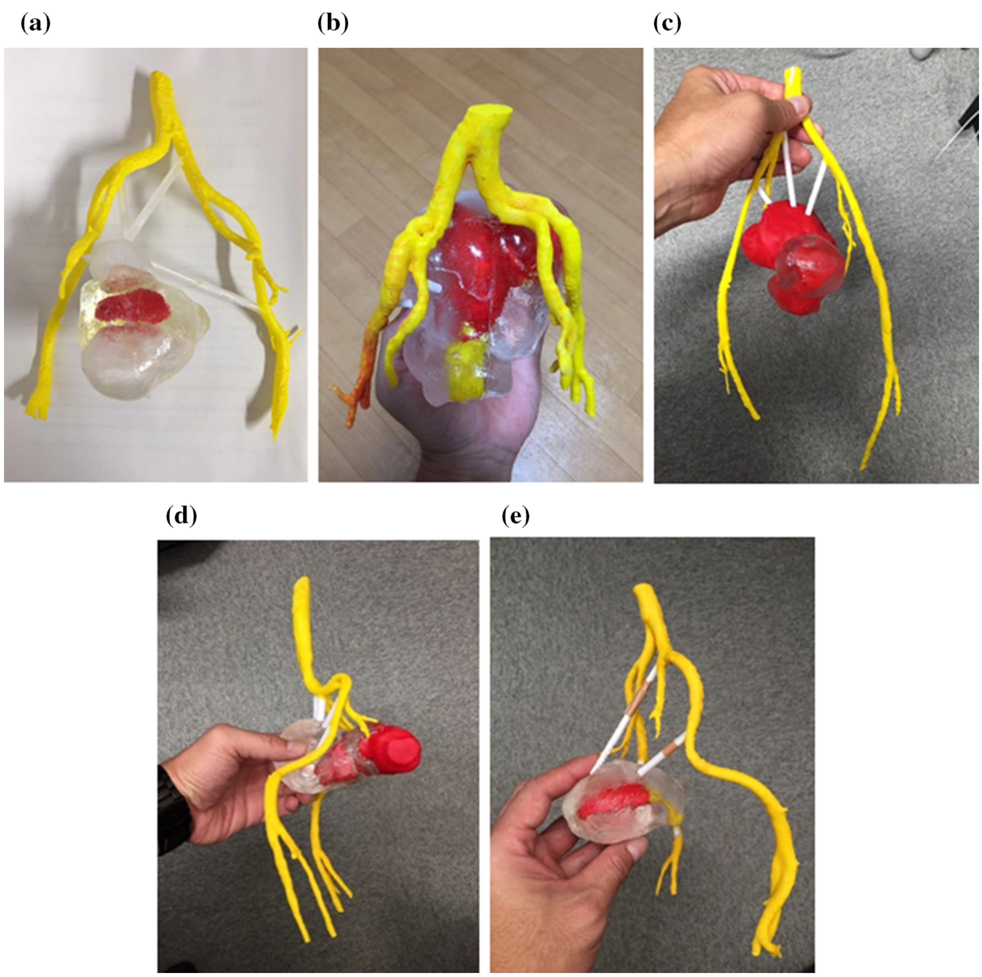
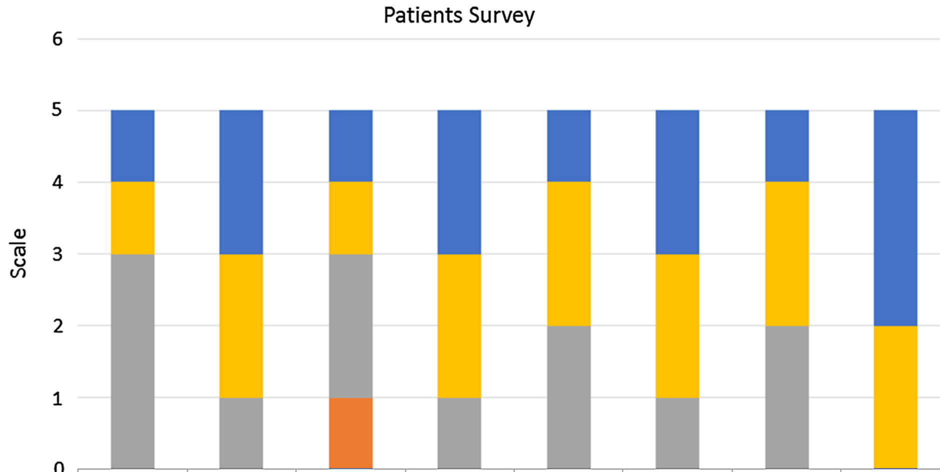


Fig. 3 Personalized uterine 3D physical models of the five uterine cancer surgical removal cases. Uterus (*transparent*), endometrium (*light yellow*), endometrial cancer (*red*), and blood vessels (*yellow*). **a** Case 1, **b** case 2, **c** case 3, **d** case 4, and **e** case 5

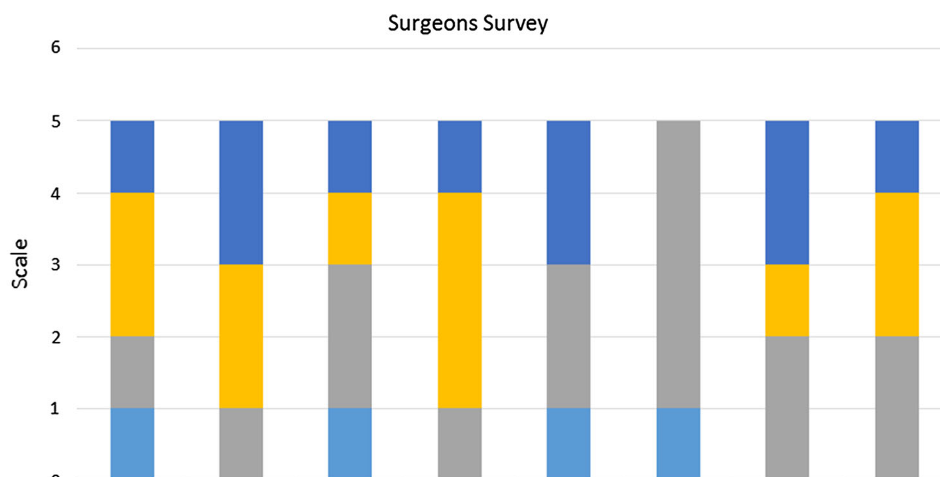


	Q1	Q2	Q3	Q4	Q5	Q6	2D	3D Model
Excellent	1	2	1	2	1	2	1	3
Very Good	1	2	1	2	2	2	2	2
Good	3	1	2	1	2	1	2	0
Average	0	0	1	0	0	0	0	0
Poor	0	0	0	0	0	0	0	0

Overall Evaluation

Poor Average Good Very Good Excellent

Fig. 4 Results of patient acceptance survey of uterine 3D physical models compared with 2D MR images. Designed for understanding of the disease (Q1 and Q2), explanations of surgical procedure (Q3 and Q4), and explanation about risk or complications (Q5 and Q6). Q1, 3, and 5 for 2D MR images and Q2, 4, and 6 for 3D models



	Q1	Q2	Q3	Q4	Q5	Q6	2D	3D Model
Excellent	1	2	1	1	2	0	2	1
Very Good	2	2	1	3	0	0	1	2
Good	1	1	2	1	2	4	2	2
Average	0	0	0	0	0	0	0	0
Poor	1	0	1	0	1	1	0	0

Preoperative (Q1-Q3), Postoperative (Q4-Q6) Overall Evaluation (2D & 3D Models).

Poor Average Good Very Good Excellent

Fig. 5 Surgeons' acceptance survey of uterine 3D physical models compared to 2D MR images. Questions concern anatomic position of relation gap (Q1), preoperative explanation to patients (Q2), operation plan (Q3), determining the size of the tumor (Q4), the positional relationship between the uterus and the tumor (Q5), and the positional relationship between the blood vessels and the tumor (Q6)

patient after image registration) is shown in Fig. 6. The mean errors of the original uterine MRIs versus uterine 3D physical models for case 1, case 2, case 3, case 4, and case 5 were 1.19 mm (3.50 pixels), 1.94 mm (5.73 pixels), 1.49 mm (4.37 pixels), 2.22 mm (6.55 pixels), and 1.75 mm (5.14 pixels), respectively. A slight gap on the surface between the original uterine MRIs versus uterine 3D physical models, with an average of ±1.71 mm (5.06 pixels), was observed.

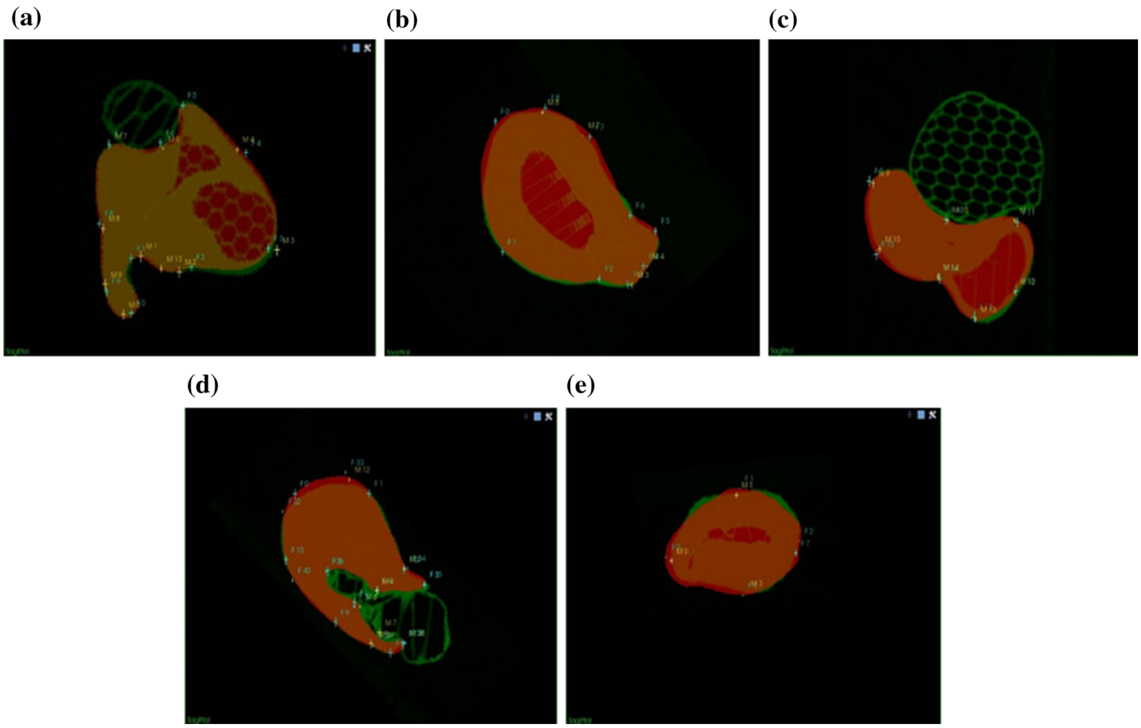


Fig. 6 Mean value of the errors [original uterine MRI vs. uterine 3D physical model (CT images)]. **a** Case 1: 1.19 mm (3.50 pixels). **b** Case 2: 1.94 mm (5.73 pixels). **c** Case 3: 1.49 mm (4.37 pixels). **d** Case 4: 2.22 mm (6.55 pixels). **e** Case 5: 1.75 mm (5.14 pixels). *Red color* marks original uterine MRI (fixed data), and *green* indicated the 3D physical model CT images

4 Discussion

From the experimental results, we confirmed that the proposed approach successfully created personalized uterine 3D physical models that accurately reproduced the anatomic structures and lesions on MR images. Due to the deformation of the elastic material in the 3D physical model caused by its weight, there was an error (about 1.19–2.22 mm shift) in the gap on the surface of the uterine body. This deformation was acceptable for uterine surgery, because the actual uterine body is also deformed when the position of the uterine was changes. We confirmed that the spatial gaps (distances) between the lesions and the endometrium were preserved accurately, as demanded by the surgeons. The transparency of the models was also sufficient to allow the views of the 3D structures inside the uterine body in any direction, and the elasticity and shape of the models were similar to those of the actual uterine body. The cost of the 3D model was low, because we used materials that are routinely used in hospitals [9, 10]. Furthermore, the materials used for 3D printing can be recycled.

The reliability and usefulness of our personalized uterine 3D physical models were demonstrated by in the evaluation questionnaire and by image-based evaluation of the accuracy results. From the feedback evaluation, as shown in Figs. 4 and 5, we confirmed that all patients were satisfied with the uterine 3D physical models compared to 2D MR images during the explanation from the surgeons for their understanding about the disease, surgical procedures, and risk of complications. From the surgeons' perspective, also, we confirmed that the overall evaluation of the 3D physical models was favorable, especially for assisting in the preoperative explanation to patients and for obtaining information on the positional relationship between the uterus and the tumor. We can conclude that the surgeons' experience was not given a significant impact compared to the shape and condition of the patient data itself in this survey. Regarding the image-based evaluation result shown in Fig. 6, our personalized uterine 3D physical models showed a slight difference in gap measurement of the gap between the original uterine body on the original MR images of the patients and the uterine 3D physical models on CT images, with an average of ± 1.71 mm (5.06 pixels).

The major limitation of this study is the long time (about 3 to 5 days) required for model generation. However, this is not a large problem in uterine surgery, which is rarely performed on an emergency basis. Another limitation is the difficulty to printing a thin blood vessels and a wide range of the human anatomy. This problem can be solved with help of the progress made with the next generation of 3D printing devices. As to future work, we plan to improve the way of mixing the polyol with isocyanate material and the casting technique to increase transparency and to test the surgical simulation by cutting the models. Further experiments will be performed for validation of the usefulness of physical models.

5 Conclusion

We propose an approach for generating personalized uterine 3D physical models using 3D printing and mold casting methods based on 3D MR images. Each model generated was an exact replica of target anatomic structures, with the advantages of proving the actual scale of the actual uterine body, transparency for easy 3D observation, an elastic property that is similar to that of the actual uterine body, and mobility compared to the conventional 3D visualization method. The low cost of the materials used for model production provides the possibility for daily use in the hospital as opposed to 3D visualization which requires a high-performance computer process. The survey evaluating the five surgical cases showed that our 3D physical models were not only useful for planning by surgeons, but also helpful for communicating with and providing explanations to patients.

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Compliance with ethical standards

Conflict of interest The authors have declared that no competing interests exist.

Statement of human rights and informed consent This study was approved by the human research committee of the institutional review board and complied with the guidelines of the Health Insurance Portability and Accountability Act of 1999. Written informed consent was obtained, from the five patients with endometrial cancer.

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