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ORIGINAL COMMUNICATION

Surface Model of the Gastrointestinal Tract Constructed From the Visible Korean

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Most currently available three-dimensional surface models of human anatomic structures have been artistically created to reflect the anatomy being portrayed. We have recently undertaken, as part of our Visible Korean studies, to build objective surface models based on cross-sectional images of actual human anatomy. Objective of the present study was to elaborate surface models of the GI tract and neighboring structures that are helpful to medical simulation. The GI tract from stomach to anal canal was outlined and reconstructed from sectioned images of the Visible Korean (a computer database containing the digitized transverse sectional images of a 33-year-old Korean man). The outlining procedure was supported by computational filtering and interpolation using commercially available software. The GI tract was divided into several parts, and each of these parts was surface reconstructed and then united with neighboring parts to produce a surface model of the complete GI tract. Surface models of about 100 neighboring structures were also prepared. The surface models produced will hopefully facilitate the development of interactive simulations for a variety of virtual abdominal surgical procedures or other educational programs. In addition, it is hoped that the improved outlining and surface reconstruction techniques described will encourage other researchers to construct similar surface models based on images obtained from different subjects. Clin. Anat. 22:601–609, 2009. © 2009 Wiley-Liss, Inc.

Key words: surface models; gastrointestinal tract; Visible Korean; outlining; surface reconstruction; abdominal structures

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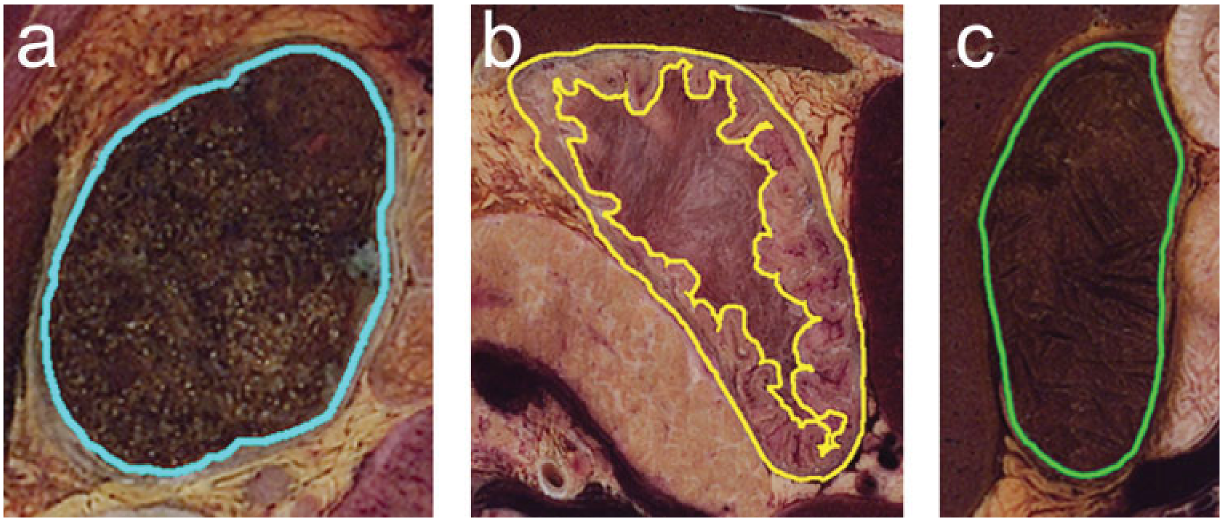

Fig. 1. **a:** Mural outline of the large intestine. **b:** Mural and luminal outlines of the stomach. **c:** Luminal outline of the gallbladder. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

INTRODUCTION

Surface models are hollow 3-D images, and thus, have much smaller file sizes than volume models. This means that surface models can be distributed, opened, rotated, and modified in real time, even online, and the manipulation can be done without functional restriction using popular commercial software (Park et al., 2007). In general, volume models, which contain considerable information, are favored by medical experts; however, surface models are more useful for educational and surgical training purposes. For example, surface models of the lumbar region enable virtual lumbar puncture simulation by allowing a virtual needle to be interactively inserted through multiple tissue layers and into the subarachnoid space (Park et al., 2008).

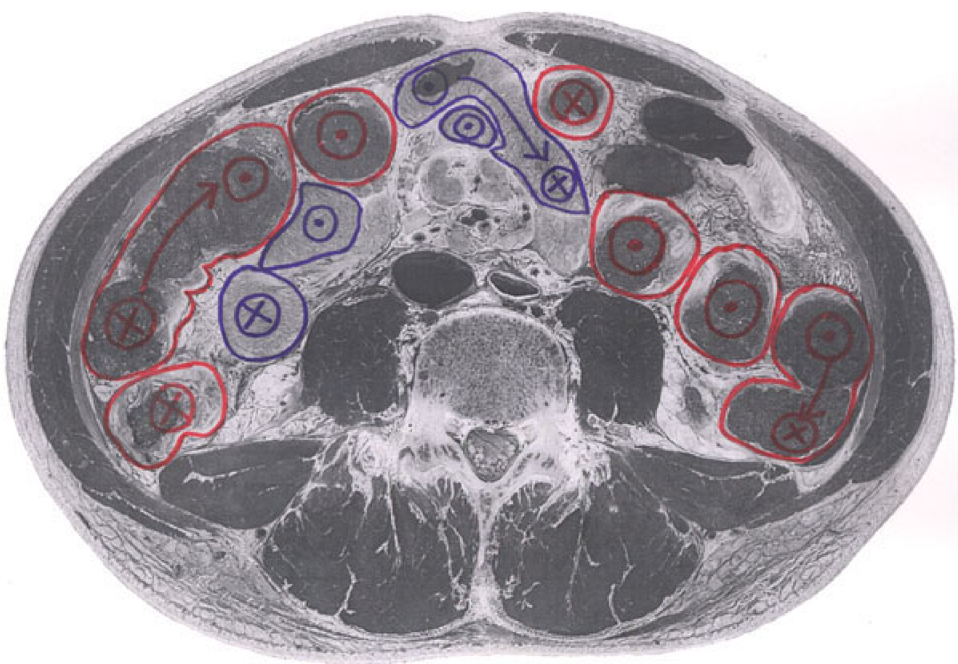

Fig. 2. Gastrointestinal tract, which is denoted on paper by direction signs. [Color figure can be viewed in the online issue, which is available at www. interscience. wiley.com.]

TABLE 1. Gastrointestinal Tract and Neighboring Abdominal Structures That Were Outlined, Surface Reconstructed, Made Into Surface Models

Systems	Structures outlined and surface reconstructed	Structures made into surface models
Digestive	Gastrointestinal tract[a]	Esophagus, stomach, duodenum, jejunum, ileum, cecum, appendix, ascending colon, transverse colon, descending colon, sigmoid colon, rectum, anal canal
	Gastrointestinal tract[b]	Esophagus, stomach, duodenum
	Liver, pancreas, pancreatic duct[b]	(Equal)
	Bile duct[b]	Common hepatic duct, cystic duct, gallbladder, common bile duct
Vascular	Arteries[b]	Abdominal aorta, celiac trunk, common hepatic artery, proper hepatic artery, right hepatic artery, cystic artery, left hepatic artery, gastroduodenal artery, superior pancreaticoduodenal artery, splenic artery, left gastric artery, superior mesenteric artery, ileocolic artery, right colic artery, middle colic artery, inferior mesenteric artery, left colic artery, sigmoid artery
	Portal veins[b]	Superior mesenteric vein, splenic vein, hepatic portal vein, right branch, left branch
	Systemic veins[b]	Hepatic veins, inferior vena cava
Muscular	Diaphragm, pelvic diaphragm, urogenital diaphragm, rectus abdominis muscles (2), external oblique muscles (2), internal oblique muscles (2), transverse abdominal muscles (2)	(Equal)
Skeletal	Thoracic vertebrae (5), ribs (24), lumbar vertebrae (5), sacrum, sternum, hip bones (2)	(Equal)
Articular	Intervertebral discs (10)	(Equal)
Integumentary	Skin, umbilicus	(Equal)
Total	(68)	(107)

(Equal) means the same structures as the left ones. (Number of the structures rendered, if more than one).
[a]Mural contours of the structures outlined.
[b]Luminal contours of the structures outlined.

Accordingly, we considered that a surface model of the gastrointestinal (GI) tract, accompanied by those of related abdominal structures, would aid understanding of the anatomy of the digestive system and could be used for producing a virtual abdominal operation system. Currently available three-dimensional surface models have been generated by artists with knowledge of the anatomy. Thus, we undertook to build objective surface models based on scientific data by outlining structures in serially sectioned images of the human abdomen, stacking these outlines, and smoothing discontinuities using a polygon-based surface reconstruction method (Park et al., 2007).

Visible Korean data contains 0.2-mm-sized pixels and real body color information, and thus, offers a means of constructing such models (Park et al., 2005b, 2006). However, it is extremely difficult to acquire outlined images and surface models of the entire GI tract because of its convoluted course in sectioned images. Therefore, we improved upon a previously described technique of outlining and surface reconstruction using commercial software (Park et al., 2005a, 2007).

The purpose of this research was to construct surface models of the GI tract and neighboring structures that can be used to train medical students and doctors. The improvements made in the outlining and surface reconstruction technique will make it easier to construct surface models from other serial images such as CT and MR images.

MATERIALS AND METHODS

Outlining

Sectioned images of an entire nonembalmed male cadaver (age, 33 years; height, 1.64 m; weight, 55 kg) had been acquired at 0.2-mm intervals (pixel size, 0.2 mm; resolution, 3,040 $\times$ 2,008) during our previous Visible Korean study (Park et al., 2005b, 2006). From these, 412 images, at 1-mm intervals, were chosen from the abdomen, pelvis, and perineum regions and contained profiles of the GI tract.

Sixty-eight structures were selected for outlining. The GI tract was outlined along its mural (wall) contour (Fig. 1a). The esophagus, stomach, and duo-

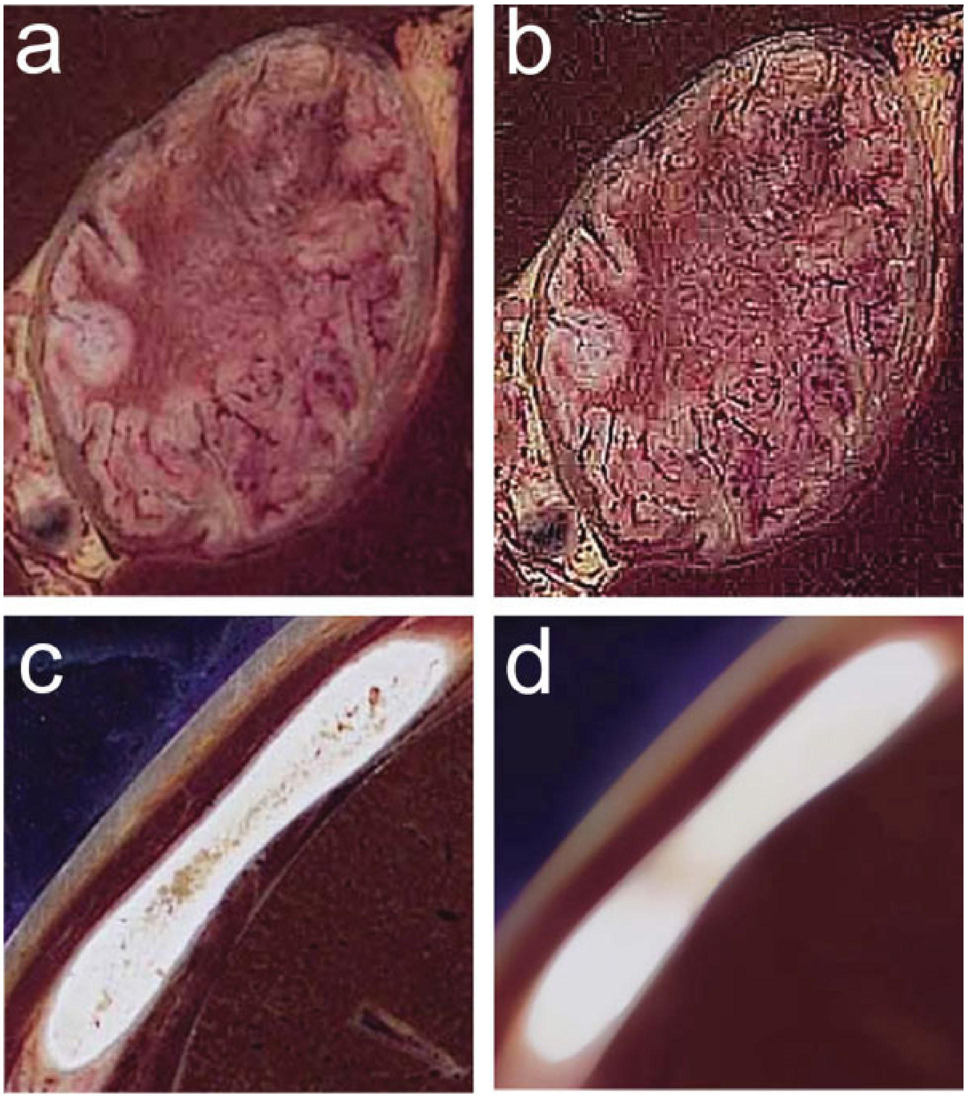

Fig. 3. **a:** A sectioned image of the stomach. **b:** The same image after applying the ''sharpen'' filter in Combustion to clarify mural contour. **c:** A sectioned image of bone. **d:** The same image after applying the ''median'' filter. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

denum were additionally outlined along their luminal contours (Fig. 1b) as were the pancreatic duct, bile duct, gallbladder, and blood vessels (Fig. 1c; Table 1).

It was difficult to identify the complete length of the GI tract despite the quality of the sectioned images. Therefore, we adopted the following procedure. Images of sections were first printed onto paper. The GI tract was then traced either proximal to distal or distal to proximal by referring to an atlas of sectioned images (Spitzer and Whitlock, 1998). Every identified part of the GI tract was denoted on the paper with arrows, indicating the proximal to distal direction. The process was repeated until the entire GI tract was marked on paper (Fig. 2).

While referring to the paper images, mural outlines of the GI tract were then drawn on a computer screen. Although some mural outlines were distinct in sectioned images, because of the presence of visceral peritoneum, most outlines had to be drawn manually. To enhance automation, sectioned images were ''sharpen'' or ''median'' filtered on Autodesk Combustion® version 4 (Combustion) (Fig. 3).

Morphological features of the GI tract show only subtle changes in adjacent 1-mm sections. Therefore, interpolation was used to reduce the tedium associated with this work. For instance, a descending portion of the GI tract was delineated in two sectioned images at 10-mm interval in Combustion. Then, using the ''animate'' tool in Combustion, automatic interpolation was performed to create nine intervening outlines at 1-mm intervals (Fig. 4). When the created outlines did not fit the GI tract on

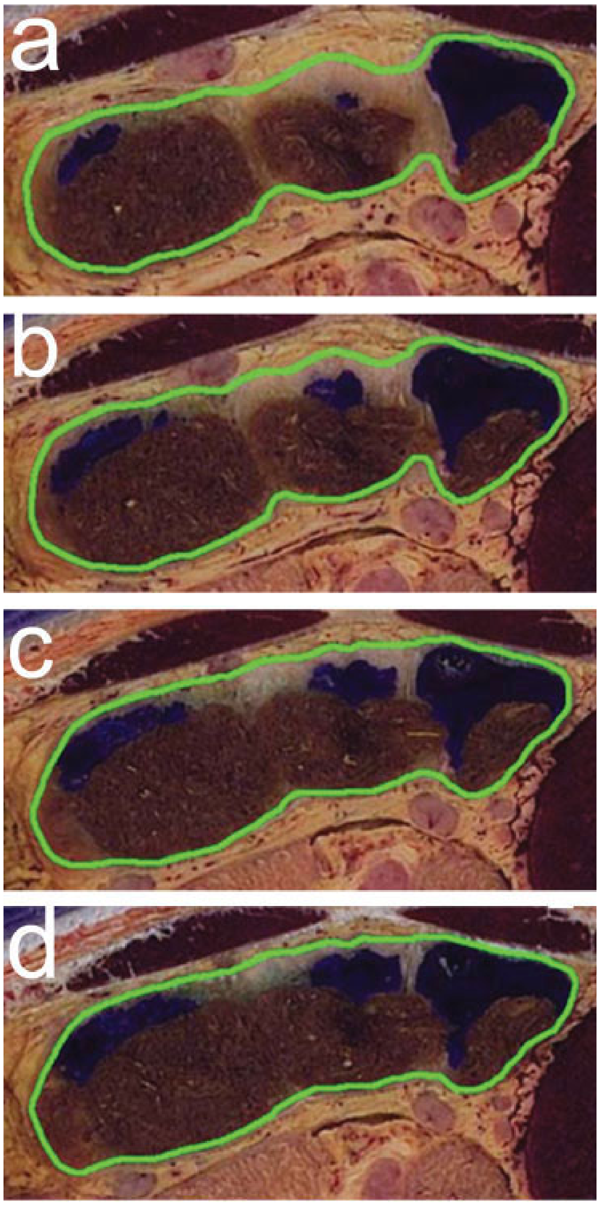

Fig. 4. **a,d:** Manually drawn outlines of the large intestine. **b,c:** Outlines obtained automatically by interpolation. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

sectioned images, they were manually revised. Outlines produced in Combustion could not be stacked for surface reconstruction, and thus, were saved in Photoshop data (PSD) file format by way of tag image file format (TIFF).

Because of its complexity, the GI tract could not be surface reconstructed as a single unit. Instead, it was divided into several parts, namely, descending, ascending, inferiorly curved, superiorly curved, and horizontal parts. Outlines of the GI tract were then grouped by parts to construct part surface models (Fig. 5a).

Surface Reconstruction

Surface reconstruction of the stomach, the first descending portion of the GI tract, was performed as previously described (Park et al., 2007). Outlines of the stomach were first stacked in Alias Maya® version 7 (Maya) (Fig. 6a), and gaps between stacked outlines were filled with polygons in Rhinoceros Rhino® version 4 (Rhino) (Fig. 6b). Outlines were then deleted and surface imperfections were corrected in Maya (Fig. 6c).

Similarly, surface models of the other GI tract parts were also constructed. In Rhino, surface models of all parts were united using the ''union'' command to generate a surface model of the whole GI tract (Figs. 5b and 7a). Then by using the ''cut faces'' tool in Maya, the surface model of the whole tract was separated into 13 surface models of named structures; i.e., esophagus, stomach, duodenum, jejunum, ileum, cecum, appendix, ascending colon, transverse colon, descending colon, sigmoid colon, rectum, and anal canal (Fig. 7). In addition, surface models of 91 other structures such as liver, pancreas, portal triad, muscles, bones, and skin were also created. Then, in a Maya file, using Maya binary (MB) file format, 107 layers were made, and named using the terms in Terminologia Anatomica (FCAT, 1998; Moore et al., 2009) (Table 1). Subsequently, the surface model of each structure was placed in its own layer to produce assembled surface models (Figs. 8 and 9).

In addition, we built a draft volume model of the GI tract for comparison purposes. Initially, intervals and pixel sizes in sectioned images were increased from 0.2 mm to 1 mm, and regions beyond the GI tract in sectioned images were deleted using the outlined images (Park et al., 2005a). Then, using Able Software 3D-Doctor® version 3.5, sectioned images were stacked and reconstructed using a volumetric reconstruction technique to acquire a volume model with 1-mm voxel size and real color (Fig. 10b and 10d).

RESULTS

The GI tract from the stomach to the anal canal was traced without interruption onto paper (Fig. 2). This was made possible because we used high-quality sectioned images of 0.2-mm pixel size in 24-bit color (Park et al., 2006).

Outlining was performed semiautomatically using software filters. It was found that the ''sharpen'' function in Combustion increased color differences, which allowed more automated outlining of the GI tract and muscles, which had colors close to those of neighboring structures (Fig. 3a and 3b). ''Median'' filtering was used to reduce noise of structure color and was found to be useful for increased automation of outlining the bile duct, blood vessels, and bones, which had colors that were quite different from those of neighboring structures (Fig. 3c and 3d). Sharpen and median filtering in Combustion was conducted at 50%.

Outlining was performed more automatically by interpolation (Fig. 4). In the case of vertically dis-

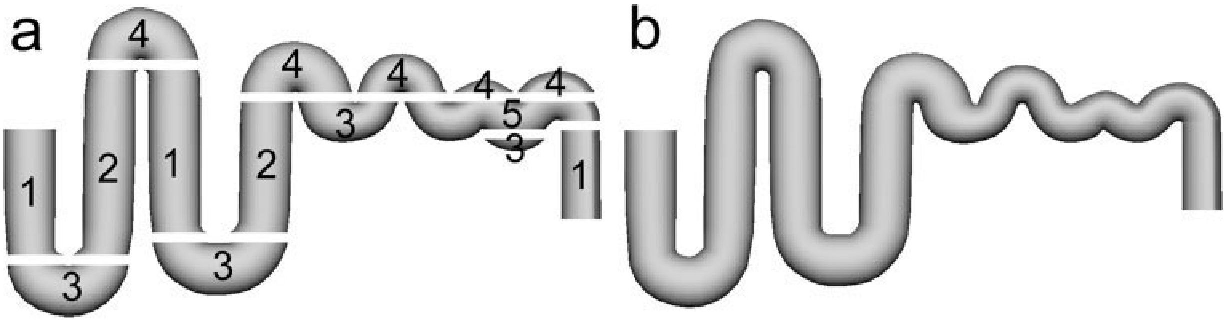

Fig. 5. **a:** Schematic of the gastrointestinal tract divided into (1) descending parts, (2) ascending parts, (3) inferiorly curved parts, (4) superiorly curved parts, and (5) horizontal parts. **b:** Reunification of the divided parts.

posed structures, which changed little in adjacent sections, interpolation was done to create even 19 intervening outlines, and thus, the effort and time required for outlining were greatly reduced. On the other hand, in the case of horizontally disposed structures, which changed abruptly in adjacent sections, interpolation was rarely possible.

One-hundred seven surface models of the GI tract and significant abdominal structures (MB files; 50 MB) were prepared (Table 1). The surface models produced were accurate enough to visualize the original shapes and positions of the structures (Fig. 9). For example, retroperitoneal organs (duodenum, ascending colon, descending colon, rectum) were found to be posterior when viewed laterally (Fig. 10c). The spatial disposition of the portal triad (common bile duct, located on the right side; portal vein, located posteriorly) is shown in Figure 8. The objectivity of the surface models was confirmed by the similarity between the surface model of the GI tract and its volume model (Fig. 10), both of which were derived from the ''Visible Korean.'' The objectivity was also convinced by superimposing the surface model upon the original sectional images (Fig. 11). Furthermore, in the surface model of the liver, a variation was observed; the left hepatic vein had a wider diameter than the sum of the diameters of the right and intermediate hepatic veins.

DISCUSSION

Creation of surface models of the GI tract requires sectioned images of a cadaver because the mural contour of this system cannot be readily outlined in abdominal CT or MR images, though portions of the lumen of the tract could be delineated by using contrast medium or gas. In addition, CT peritoneography is not a solution for delineating the GI tract especially because portions of it are retroperitoneal. Furthermore, when such techniques are used in the living, the GI tract is obscured because of the GI motion artifacts and the effect of lung movement during image scanning. Consequently, sectioned images provide the only means for accurately delineating the GI tract.

In the present study, we utilized the popular commercial software packages Combustion, Maya, and Rhino, because their availabilities allow other investigators to perform outlining and surface reconstruction on a personal computer without requiring the

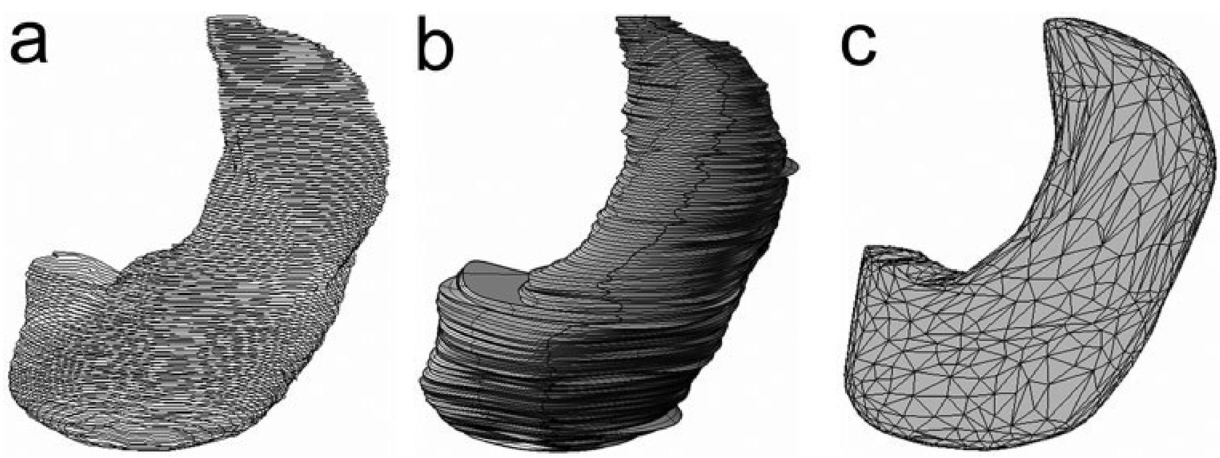

Fig. 6. **a:** Stacked outlines of the stomach. **b:** Surface model with stacked outlines preserved. **c:** Surface model with stacked outlines deleted.

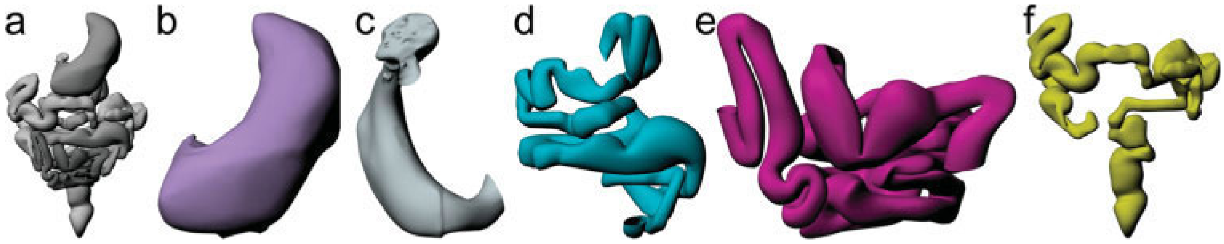

Fig. 7. Surface models of the (**a**) gastrointestinal tract, (**b**) stomach, (**c**) duodenum, (**d**) jejunum, (**e**) ileum, and (**f**) large intestine. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

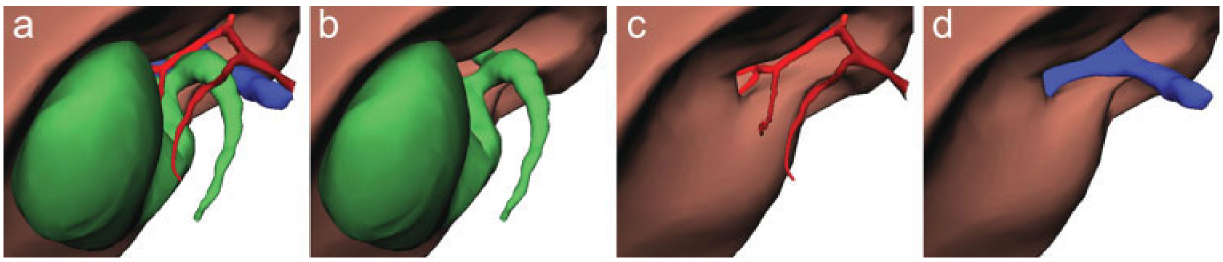

Fig. 8. Surface models of extrahepatic structures; (**a**) the portal triad, (**b**) bile duct, gallbladder, (**c**) hepatic artery, and (**d**) portal vein. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

assistance of computer engineers. Using these packages, investigators can take advantage of user-friendly commands and obviate debugging procedures to produce surface models from sectioned images of the Visible Human Project (Spitzer and Scherzinger, 2006), the Chinese Visible Human (Zhang et al., 2006), or the Virtual Chinese Human (Yuan et al., 2008), or from CT and MR images.

This study made improvements to the outlining and surface reconstruction methods used in our previous studies (Park et al., 2005a, 2007; Uhl et al., 2006). Outlining was done after first tracing by hand the GI tract in various sections onto paper (Fig. 2). This process might be viewed as unnecessary, but because of the complexity of the GI tract, it was found to be essential. Unlike sectioned images on a

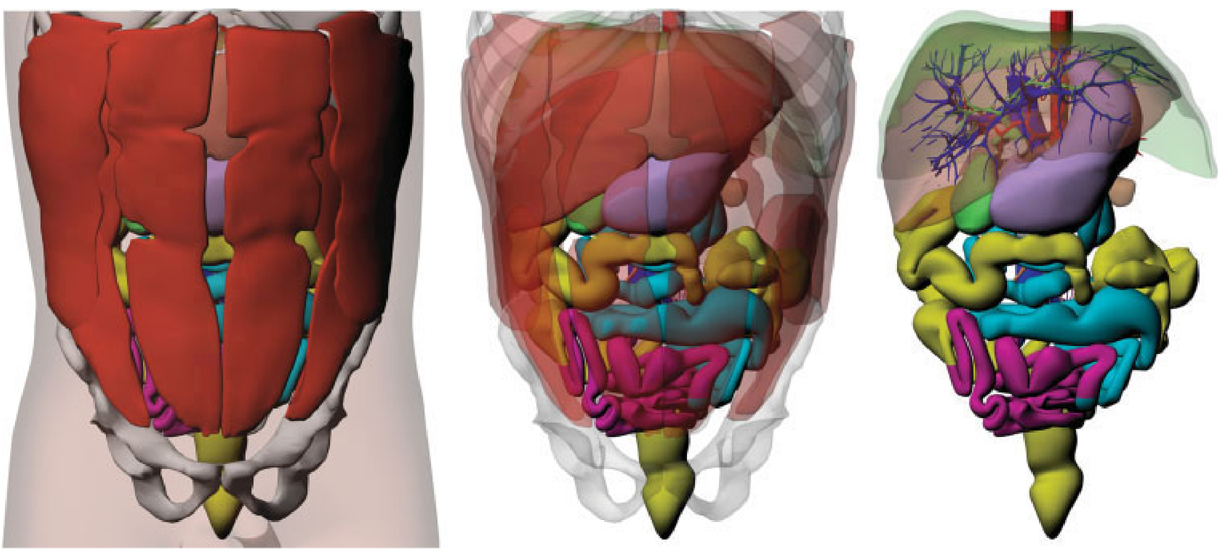

Fig. 9. Assembled surface models of the gastrointestinal tract and neighboring structures. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

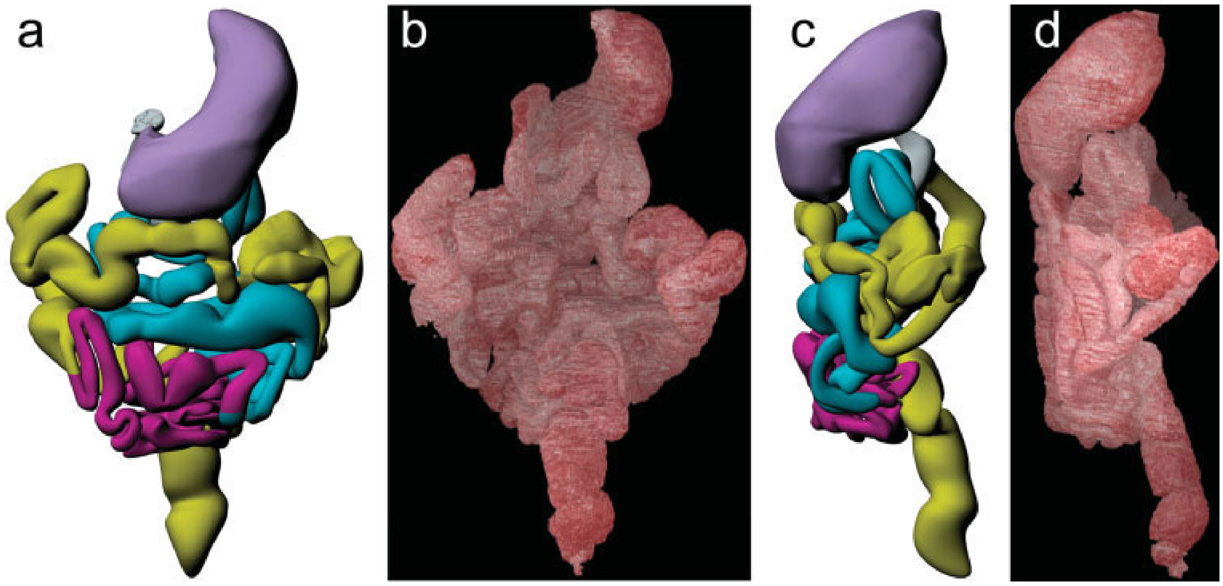

Fig. 10. Three-dimensional models of the gastrointestinal tract. Anterior view (**a**) of a surface model and (**b**) of a volume model. Left lateral view (**c**) of a surface model and (**d**) of a volume model. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

computer monitor, paper is easily manipulated during the tracing procedure.

Unlike CTs and MRIs, sectioned images are in real color, which allows even small structures to be identified (Spitzer et al., 1996). But real color does not always clearly demarcate the contours of structures (Park et al., 2005a). To improve automation during this outlining process, we tried various types of filters and eventually found that different filters are required for different structures (Fig. 3). Other types of filters, as well as, modifying brightness and contrast might also be useful to better delineate structures in color images.

Outlining can also be done more automatically by interpolation. Usually, structural features in adjacent sections change only gradually (the section interval used in the present study was 1 mm), and these gradual changes may be suitable for image process-

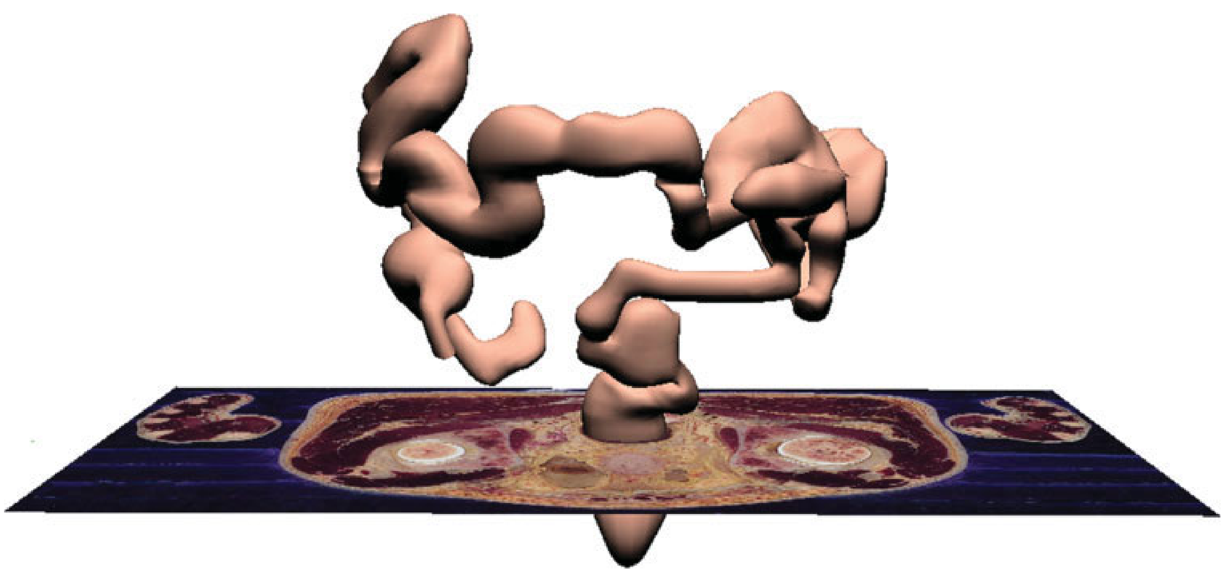

Fig. 11. Surface model of the large intestine, superimposed upon a sectioned image. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

ing interpolation using commercial software like Combustion (Fig. 4). It would be further challenging to use interpolation to create outlined images at 0.2-mm intervals, the same intervals of the sectioned images in the Visible Korean (Park et al., 2005b). This should produce surface and volume models of even greater quality.

The GI tract was found to be too complex for surface reconstruction processing as a single unit, and therefore, it was divided into several parts. After reconstructing the surfaces of each part using our previously described procedure (Park et al., 2007), individual parts were combined to produce a surface model of the whole GI tract (Figs. 5, 6, and 7). However, it should be mentioned that our surface models have their limitations. Structures like small diameter arteries could not be surface reconstructed because they were identified and outlined at 1-mm intervals. Accordingly, the next stage in this research will involve the identification and manual outlining of small structures in the original sectioned images at 0.2-mm intervals. This will demand considerable effort.

As further inquiry for the realistic medical simulation, following trials are considered. Small but significant structures, barely identifiable in sectioned images (e.g., the accessory pancreatic duct), are manually drawn on Maya to acquire additional surface models. Stereoscopic drawings are obtained using the ''sphere'' command and the ''edit mesh'' tool in association with surrounding structures. In addition, it might be valuable to compose software that builds a volume model of an organ (e.g., the liver) from sectioned and outlined images and that extracts the surface texture of the organ from the volume model. Then on Maya, surface model of the organ might be coated with the surface texture.

A surface model of the complete GI tract has also been constructed using Visible Human Project data (http://visiblehuman.epfl.ch) (http://www.voxel-man.de/gallery/). Unfortunately, the details of the methodologies employed to produce them, unlike that presented here, are not readily available to investigators, and these models do not lend themselves to easy modification for production of medical training programs.

All Visible Korean data, including sectioned images, outlined images, and surface models, such as the 107 surface models of the GI tract and neighboring structures prepared during this work, are available free of charge for noncommercial applications. After obtaining permission to use data from the person responsible (currently, Sang-Ho Lee, Korea Institute of Science and Technology Information, Republic of Korea; shlee@kisti.re.kr), data will be provided to users worldwide either on- or offline. The MB file of the assembled surface models can be converted into drawing exchange format (DXF) files of individual surface models. DXF files containing morphological and locational information are available in commercial softwares such as Discreet 3ds MAX® and Autodesk AutoCAD®, and on free software packages such as Autodesk Volo View3® and Brava Free DWG Viewer®.

Surgical training simulations of interest that could be produced using these GI surface models include virtual gastrojejunostomy, virtual laparoscopic cholecystectomy, and virtual endoscopic retrograde cholangiopancreatography. Other educational tools could also be devised, such as illustrating the embryonic development of the GI tract. It is hoped that the improved outlining and surface reconstruction technique described here will help other investigators develop surface models from serial images they have acquired or that acquisition of some of our surface models will stimulate creation of other virtual medical training or educational programs.

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