NAVIGATION-BASED INTELLIGENT CAD SYSTEM: NAVI-CAD

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ABSTRACT

This paper presents navigation-based intelligent computer-aided diagnosis (NavI-CAD) systems for the chest and abdomen. A NavI-CAD system assists image diagnosis and augments doctors' diagnostic processes by displaying assistance information such as positions of abnormal regions, paths to desired points, and locations of important organs around the viewing area in the navigation of a virtual human body. This system enables us to assist endoscopic examinations by combining it with an endoscope navigation system. This approach is quite innovative because it provides intelligent functions such as navigation based on anatomical analysis and fusion between real and virtual human bodies as well as abnormal region-detection functions of conventional CAD systems.

1. INTRODUCTION

Recently, imaging devices such as X-ray CT, MRI and ultra sound have made significant progress. With the development of such devices, medical images with high resolution have become available and are widely used in the clinical field. Since medical images include much information on human bodies, clinicians can make diagnoses or planning of surgical operations based on this information. However, the workload on clinicians has rapidly increased along with improved image resolution. Therefore, computer aided diagnosis (CAD) systems are expected to be developed for assisting clinicians.

Many research efforts have been reported on the development of CAD systems. The main issues in this research are development of fundamental functions such as organ segmentation, understanding of anatomical structures, abnormal shadow detection, and visualization. However, these problems have been pursued independently, and there are few systems that integrate them to the point of multi-modal resources. Therefore, integration of the relevant technologies at the meaning level will become quite important for CAD systems. This paper introduces applications of navigation-based intelligent CAD systems, or NavI-CADs, for the chest, colon, and epigastrium. Diagnosis through navigation means to diagnose a real patient by exploring the inside of his/her virtual human body (digital data of the body) stored in a computer and investigating the status of organs, soft tissues, or blood vessels carefully.We consider navigation using multi-modal images a very important concept for next-generation CAD systems, since it could enable us to understand various statuses of a human body intuitively.

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2. NAVI-CAD FOR CHEST

In our laboratory, we have been developing a NavI-CAD system for the chest based on the fusion of real and virtual human bodies. This system consists of three main functions: (1) anatomical structure analysis, (2) navigation, and (3) real time visualization. Furthermore, as an extended function, (4) bronchoscope tracking is implemented. An overview of the system is shown in Fig. 1. This system uses the ability of the anatomical structure analysis function to recognize a patient's anatomy, such as the lung, bronchus, and blood vessels, as the "*anatomical map*" of his/her body. It can navigate a user to the goal, i.e. abnormal area, while showing the current position on the map and surrounding structures of regions of interest. It also has intelligent functions such as path generation to a lesion by way of the bronchus, in a way similar to bronchoscopy, and automatic navigation by the generated path. In addition, a bronchoscope tracking function is equipped for assisting bronchoscopy in practice. As shown in Fig. 2, the system can show the current position during bronchoscopy. We explain each function below.

2.1. Anatomical Structure Analysis

Recognition and analysis of anatomical structure are indispensable for a NavI-CAD. Here, an anatomical map for navigation is generated from 3D medical images.

2.1.1. Chest organ segmentation

We segment the main organs in the chest: the lung, bronchus, aorta, pulmonary artery and veins. The lung regions are easily segmented by thresholding and connected-component analysis. Bronchial branches and bronchial wall regions are ex-

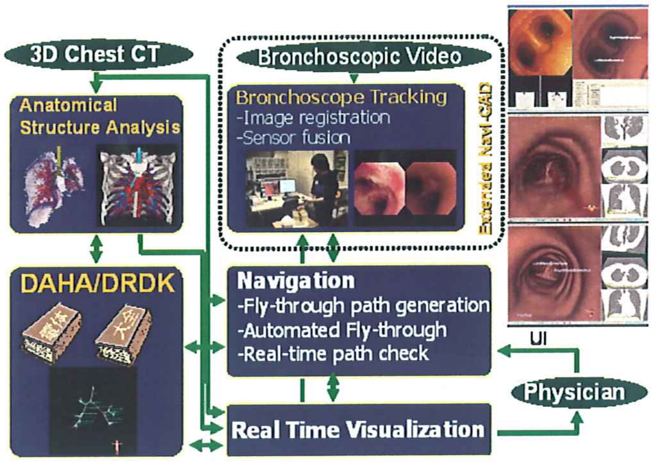


Fig. 1. System overview of NavI-CAD for chest.

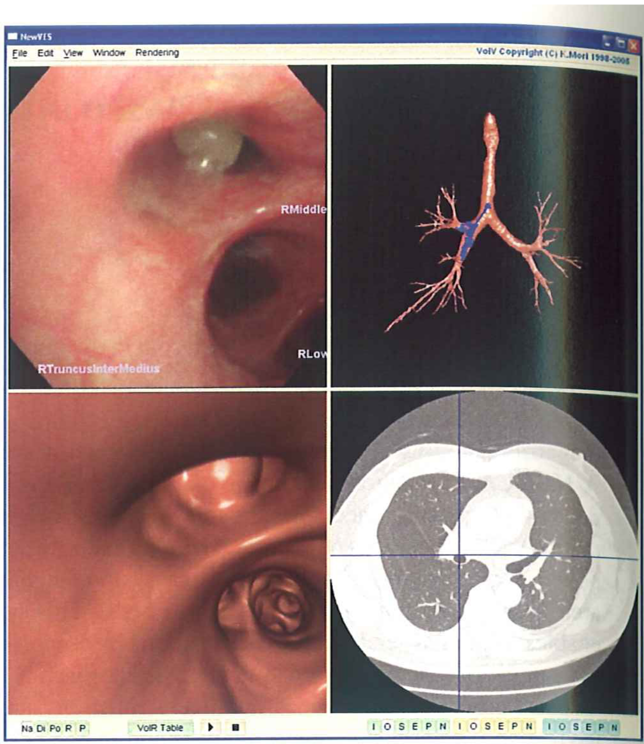


Fig. 2. Example of the system's display. Upper-left: Real endoscopic view. Anatomical names of bronchial branches now observed are overlaid on it. Lower-left: Virtual endoscopic view that corresponds to the real endoscopic view. Upper-right: Outside view of the bronchus. The trajectory of the endoscope is shown in blue. Lower-right: CT slice at the position of endoscope.

tracted by the methods in [1, 2]. These methods use a volume of interest (VOI) to segment each bronchial branch individually with adaptive thresholding, and they can also extract the bronchial tree structure simultaneously. The aorta and pulmonary artery in the mediastinum are segmented by a method using an edge detection and Euclidean distance transformation and its reverse transformation [3]. Blood vessel regions are obtained by simple thresholding, and their tree structures are extracted by a thinning algorithm as well. The pulmonary artery and vein are then recognized separately by using anatomical knowledge on the mutual relations between the bronchus and artery and the Voronoi diagram [4]. A result of organ segmentation is shown in Fig. 3.

2.1.2. *Anatomical labeling*

Anatomical names of bronchial branches are assigned by matching structural models constructed beforehand and the bronchial tree structure obtained above [5]. Several models are prepared to cope with individual branching deviation, and thus a suitable model can be selected automatically at each branching point. Figure 4 shows an example of anatomical labeling results.

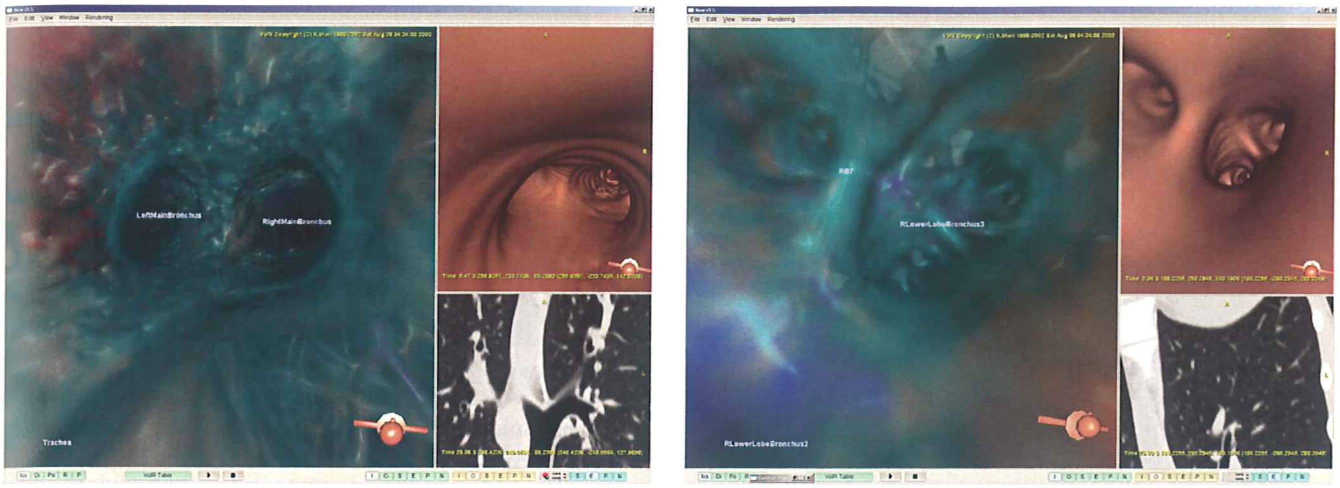
2.2. Navigation

Although much information on anatomical structure can be generated in 2.1, this is not directly linked to the assistance of a physician. The system has to recognize which organs are observed now or what organ exists further on, and it should select only useful information. We describe automatic path generation below as an example of information extraction.

A fly-through path by way of the bronchus to any desirable position that a user specifies is automatically generated for navigation. First, the closest endpoint of the tree structure to a specified point is found. Then, the route from the endpoint to the trachea is traced back on the tree structure. The fly-through path is obtained by interpolating the route by spline. We can obtain alternative representation of the path by a sequence of bronchial names as shown in Fig. 5. This representation can be useful because physicians usually recognize location in the lung by the closest bronchial name.

2.3. Real-time Visualization

Real-time visualization is achieved by the fast volume rendering method [6]. In volume rendering, various views can be drawn by setting the color and opacity table to CT values and the organs segmented in 2.1 (Figs. 3 and 6). Also, various display methods are available such as MIP (maximum intensity projection), MPR (multi-planar reconstruction), and text information like bronchial names. In MPR display, the system can draw a particular cross section whose normal vector corresponds to the up vector of the virtual camera and in which the current viewpoint is included. This allows us to observe some status ahead such as a branching structure of the bronchus and the thickness of the bronchial wall on the



(a) (b)

Fig. 6. Examples of augmented display of results of anatomical structures. (a) View near the branching point of the trachea, (b) view near the right lower lobe bronchus. The aorta (red) and pulmonary artery (blue) can be observed beyond the semi-translucent bronchial wall in the left window. Bronchial names are also displayed. The upper-right window shows the virtual endoscopic view corresponding to the left window. The lower-right one shows the MPR display near the observing point.

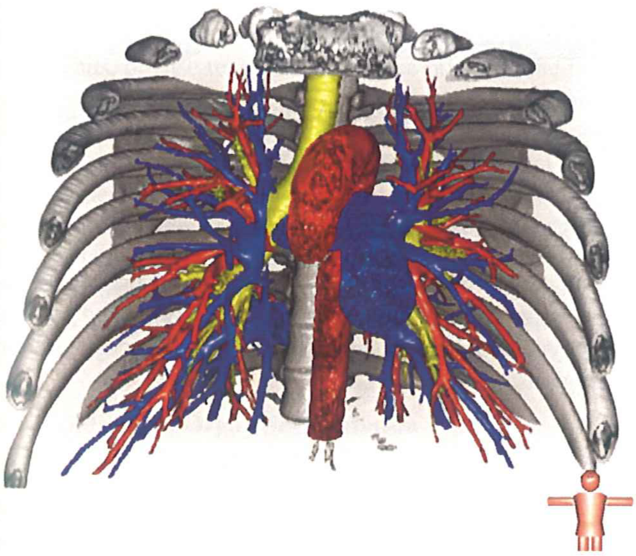


Fig. 3. Segmentation results of the chest.

cross-sectional image (Fig. 6 lower-right window).

2.4. Tracking

The bronchoscope tracking is done by using the sequentially estimated camera parameters (viewpoint and viewing direction) that generate the virtual endoscopic view most similar to the real bronchoscopic video frame. Mutual autocorrelation is used as similarity. Motion prediction by the Karman filter is implemented for faster estimation [7]. As a result of this process, a real patient body and his/her virtual body are registered with each other, and the location in the 3D CT image corresponding to the location of the real bronchoscope in the patient body can be obtained.

3. NAVI-CAD FOR COLON

We introduce a NavI-CAD system for colon diagnosis as one of the applications for the abdomen [8]. This system aids diagnosis for colonic diseases, which are increasing in Japan. The colon is a long and winding organ and has many folds in it. Therefore, even in diagnosis by virtual colonoscopy, frequent change in viewpoints and viewing directions of the virtual camera is needed to decrease oversights of lesions. This significantly increases the doctor's workload. To reduce this, the system we have developed unfolds the colon virtually, allowing us to observe a wide area of the inwall of the colon at a glance. Figure 7 shows an overview of the system. An example of the system display is also shown in Fig. 8, in which the virtual unfolded view of the colon (upper image), CPR view (middle image), the outside view of the colon (lower middle image), the virtual endoscopic view (lower left), and MPR view of CT slices (lower right) are integrated seamlessly. A colonic cancer candidate that the system detects automatically is indicated in blue. A medical doctor can detect abnormal regions easily in the VU view and reconfirm their precise shape and intensity profiles in the VE, CPR and MPR views.

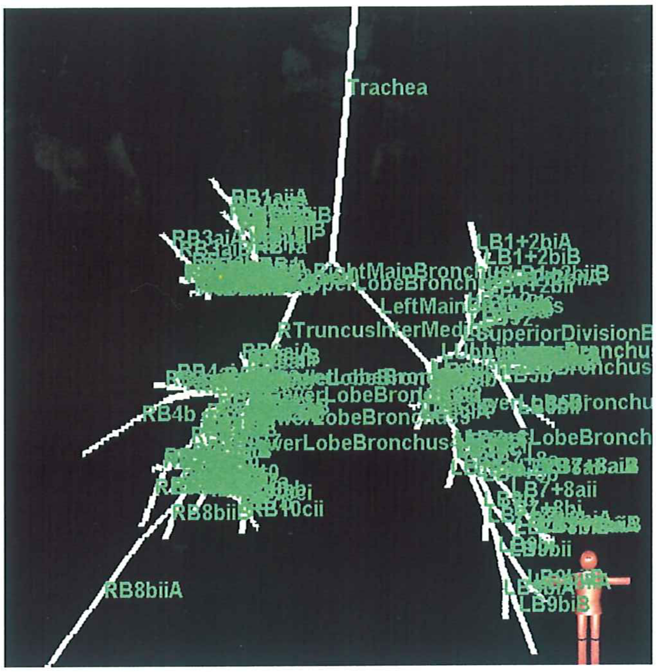


Fig. 4. Results of anatomical labeling of bronchial branches.

3.1. Colonic polyp detection

Colonic polyp candidates are detected by applying the method in [9]. In this method, protrusions on the colonic wall are detected as polyp candidates, since polyps usually form a convex shape. The shape index and curvedness [10], which are calculated from curvatures on the colonic wall, are used for shape classification.

3.2. Unfolding

A virtual unfolded (VU) view is generated by controlling ray-casting directions in volume rendering [11]. Rays are cast from the central line of the colon, which is extracted by the thinning algorithm [12] and its spline interpolation, as follows.

For each point on the central line $\mathbf{p}_i$, a ray is cast along a vertical direction to the tangent $\mathbf{t}_i$ of the central line at the voxel. Let $\mathbf{t_x}_i$ be a vector perpendicular to $\mathbf{t}_i$, and $\mathbf{t_y}_i$ be the vector perpendicular to both $\mathbf{t}_i$ and $\mathbf{t_x}_i$. Then, casting directions $\mathbf{r}^i_j (0 \le j \le m; m = 2\pi/\Delta\theta)$ at $\mathbf{p}_i$ are defined by

$$\mathbf{r}^i_j = \mathbf{t_x}_i\, cos(j\Delta\theta) + \mathbf{t_y}_i\, sin(j\Delta\theta). \quad (1)$$

That is, a VU view is generated by casting rays on an orthogonal plane Π_i toward the colonic wall side at each point $\mathbf{p}_i$ on the central line (Fig. 9). Since this unfolding is equivalent to a volumetric deformation, we can observe not only the surface of the colonic wall but also blood vessels beyond the wall on a VU view by adjusting rendering parameters (color, opacity, etc.).

Fig. 5. Navigation based on automatic path generation and anatomical labeling. The route that a user should use is listed as a sequence of bronchial names

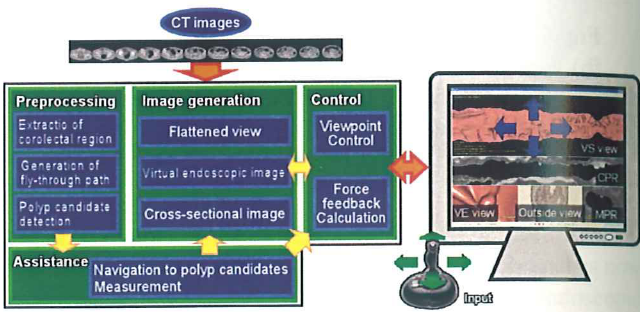


Fig. 7. System overview of NavI-CAD for colon.

3.3. Observation Assistance

Functions of this part are used to assist observation and diagnosis; these include synchronized display and coloring the polyp candidates detected automatically and the unobserved regions.

3.3.1. Synchronization of Multi Views

Let $\mathbf{p}_i$ be the point on the central line at the center of a VU view. VU, VE and MPR views are synchronized as follows. In a VE view, the viewpoint is the same as $\mathbf{p}_i$, and the view direction is set as $\mathbf{r}^i_{m/2}$ (the vector directed to the center of the VU view). The cross section that contains $\mathbf{p}_i$ is displayed.

3.3.2. Coloring polyp candidates and unobserved regions

Polyp candidates are overlaid on a VU view as well as VE and MPR views. Because of the complicated shape of the colon, there may exist oversights of polyps. Thus, detection of unobserved regions [13] is implemented in our system. A physician can understand which part he/she has not observed yet. Navigation to polyp candidates is also implemented.

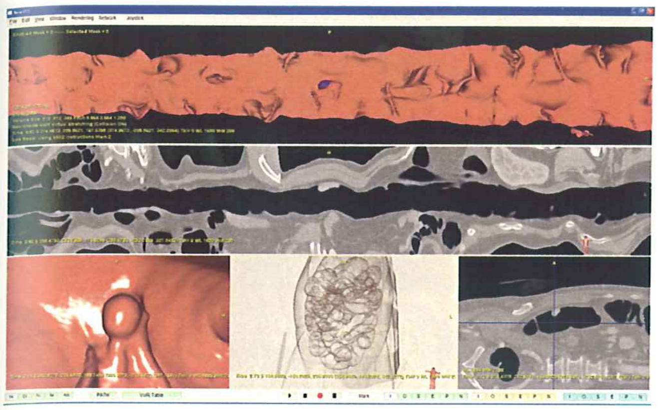


Fig. 8. Example of the system's display. Upper part: VU view. Middle part: CPR view. Lower-left part: VE view. Lower-middle part: Semi-translucent outside view of the body. Lower-right part: MPR view. All view positions are synchronized.

4. NAVI-CAD FOR EPIGASTRIUM

We have also begun to develop a NavI-CAD system for the epigastrium (upper part of the abdomen). There exist several important organs in the epigastrium, such as the stomach and liver. Thus, precise recognition of these organs is the first requirement for the Navi-CAD system for the epigastrium as well. To observe organs with a cavity, such as the stomach, stretching (or projection of) the organ to a plane, as in a pathological specimen of the stomach, is more useful and efficient than observing them as they are. This system can perform virtual stretching of organs based on image deformation. Other functions that assist laparoscopic surgery include blood vessel network analysis and virtual pneumoperitoneum. The following four sections describe these functions briefly.

4.1. Abdominal Organ Segmentation

We have developed methods for extracting abdominal organs and blood vessels from phase-contrasted abdominal CT images [14, 15]. The method in [14] uses the joint histogram of three different phases of CT images, in which characteristic intensity distribution for each organ appears. It then estimates organs' distributions by the EM algorithm. Each organ is segmented by classifying voxels to the nearest organ class in the Mahalanobis distance measure. The method in [15] uses the line enhancement filter [16] to enhance line objects like blood vessels. An example of abdominal organ segmentation is shown in Fig. 10.

4.2. Virtual Specimen

We have studied a method for generating a stretched view of luminal organs by using organ recognition and image-deformation technologies [17]. A segmented organ is modeled by hexahedra, and the model is cut and stretched based on the mass-spring model. After deformation, the original image is reconstructed using the one-to-one relationship between models before and after deformation. A virtual stretched view is then generated by rendering the reconstructed image. An example of a virtually stretched stomach is shown in Fig. 11. This kind of simulation image can be produced before resecting an organ in practice.

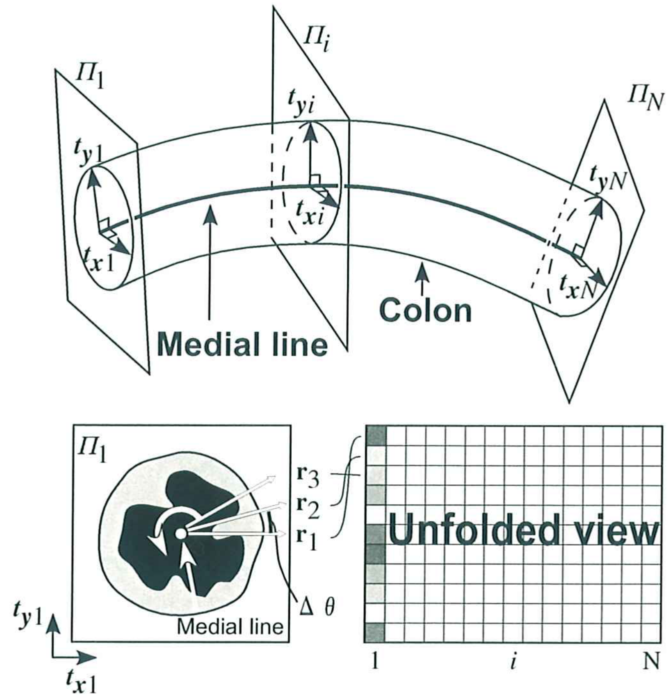


Fig. 9. Illustration of the unfolding process.

4.3. Blood Vessel Network Analysis

In surgery of the abdomen, blood vessels involving lesions are resected. However, since the method in [15] extracts many blood vessels, including thin vessels, simple visualization of them makes it very hard to understand which vessel is the target and their mutual relation. If we could select vessels of interest, it would be helpful for physicians. Thus, we have been developing a method for analyzing blood vessel networks. Figure 12 shows a result of network analysis. Peripheral blood vessels downstream from a specified point can be identified easily.

4.4. Virtual Pneumoperitoneum

The pneumoperitoneum, which makes a working space by lifting the abdominal wall by air pressure, is performed in the laparoscopic surgery. The laparoscopic surgery requires

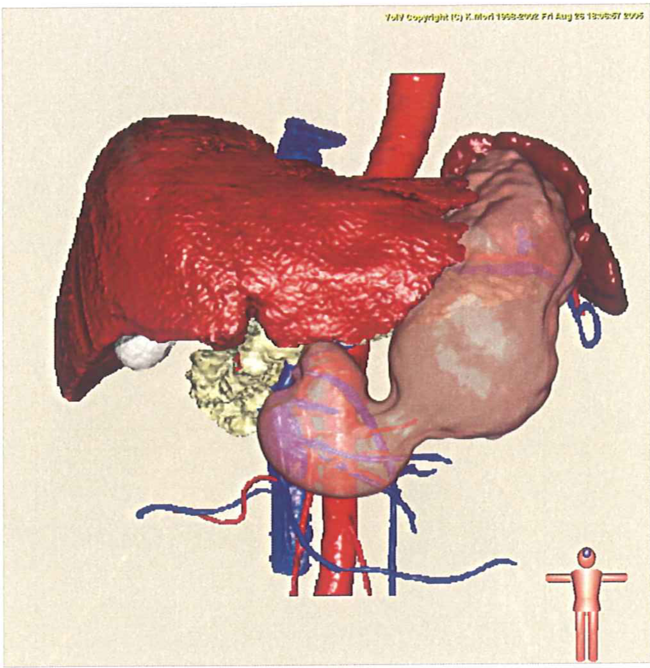


Fig. 10. Recognition results of abdominal organs and blood vessels. The liver, stomach, spleen, pancreas, gallbladder, artery, and vein are recognized.

abundant experience and high skill, because the viewable area of the laparoscope is very narrow. If simulation of the pneumoperitoneum could be carried out, a physician would understand the pneumoperitoneum state before the operation. Therefore, a virtual pneumoperitoneum would be a great help for the physician in planning the operation.

We have been developing a virtual pneumoperitoneum by segmentation of the abdominal wall and an image-deformation technique [18]. The process of the virtual pneumoperitoneum is shown in Fig. 13. Lifting the abdominal wall is simulated well from the CT image taken before performing the pneumoperitoneum.

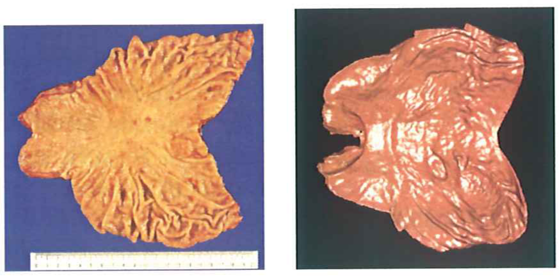


Fig. 11. Example of stretching the stomach. Left: real specimen, right: virtual specimen obtained from the CT image taken before resection.

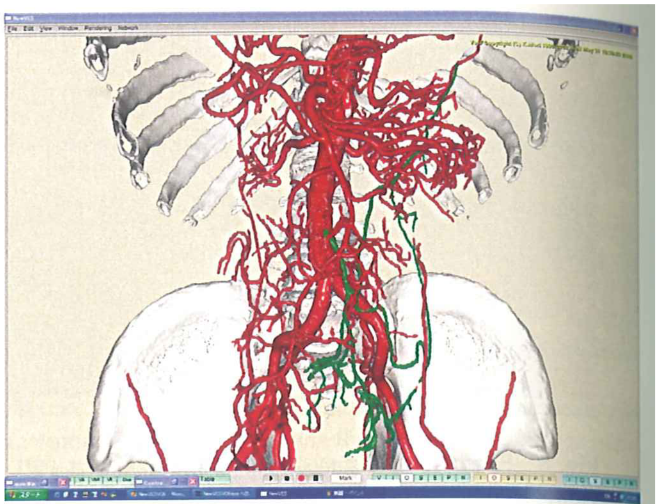


Fig. 12. Example of vascular navigation. The blood vessels of interest to the physician are emphasized.

5. CONCLUSIONS

In this paper, we introduced medical applications, called NavI-CADs, of image-processing technologies. The NavI-CAD for the chest aids image diagnosis by displaying various kinds of information such as anatomical structures and names of bronchi. It also has a function to track the bronchoscope. The NavI-CAD for the colon displays virtual unfolded, virtual endoscopic, CPR, and MPR views to aid physicians in colonic polyp detection. The NavI-CAD for the epigastrium is still under development but has some useful functions to assist both diagnosis and surgery. The NavI-CAD is an innovative system that integrates intensity, anatomical and pathological information (even from real patients) at a higher dimension, as high as the meaning level.

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Fig. 13. Deformation process of the virtual pneumoperitoneum

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