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Computer-Based Anatomy: A Prerequisite for Computer-Assisted Radiology and Surgery

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Rationale and Objectives. To show possibilities opened up by three-dimensional, computer-based models of the human body for education in anatomy, training of radiological and endoscopic examinations, and simulation of surgical procedures.

Materials and Methods. Based on three-dimensional datasets obtained from the Visible Human and/or clinical cases, virtual body models are created which provide an integrated spatial and symbolic description of the anatomy, using interactive, color/intensity based segmentation, ray casting visualization with subvoxel resolution, a semantic network for knowledge modelling, and augmented QuickTime VR movies for presentation.

Results. From these models, various radiological, endoscopic or haptic manifestations of the body can be derived. This is shown with examples from anatomy teaching, correlation of x-ray images with 3D anatomy for education in radiology, gastrointestinal endoscopy, correlation of ultrasound images with 3D anatomy in endoscopic ultrasonography, and simulation of drilling in temporal bone surgery.

Conclusion. The presented models provide a means for realistic training of the interpretation of radiologic and endoscopic images of the human body. Furthermore, certain surgical procedures may be realistically simulated. Used as a complement to the current curriculum, these models should have the potential to greatly reduce education times and costs.

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INTRODUCTION

In recent years, methods of Computer-Assisted Radiology and Surgery have opened up completely new possibilities for radiologists and surgeons. One basic prerequisite for making use of these methods is the digital, three-dimensional representation of the human body inside a computer. Two different types of such virtual body models can be distinguished:

1. General models describing the typical human anatomy. These are used for tasks like learning anatomy, or as a reference for clinical work.
2. Patient specific models, used e.g. for surgery rehearsal or intra-operative imaging.

Virtual body models are usually constructed from cross-sectional images generated by computer tomography (CT), magnetic resonance imaging (MRI), or histological cryosectioning, as in the case of the Visible Human Project of the National Library of Medicine (1, 2). They may be used interactively on a computer screen or in virtual reality environments. If these models are connected to a knowledge base of descriptive information, they can even be interrogated or disassembled by addressing names of organs (3, 4, 5). They can thus be regarded as three-dimensional anatomical atlases or a “self-explaining body”.

As a step further, integrated spatial and symbolic models of the human body may also be used to simulate various clinical procedures which are difficult to learn. In an effort to facilitate learning and reduce education times and costs, we developed various extensions to our VOXEL-MAN visualization system for education in anatomy, training of radiological and endoscopic examinations, and simulation of surgical procedures.

MATERIALS AND METHODS

Building a comprehensive model of the human anatomy requires both a spatial description consisting of three-dimensional objects, which are displayed using methods of volume visualization, as well as a linked symbolic description of relevant anatomical terms and their relations (3).

Building such an integrated model is a highly labour-intensive task, which is worth while only if the best data available are used. For general models, the highest resolution to date is provided by the Visible Human dataset, which is used as the basis for most of the applications in this paper.

In the following, the procedure to create such an integrated spatial and symbolic model is briefly described to provide a basis for the following sections. For a more detailed description, we refer to our previous publications (3, 6, 7).

Spatial Modeling and Visualization

The underlying image volume which may be the result of several pre-processing steps such as registration and scaling is segmented with an interactive tool, based on classification in color space (as for the Visible Human) or intensities (for radiological data). On one or several cross-sections, an expert marks a typical region of the organ under consideration. All voxels in the volume with similar colors or intensity values are then collected by the program and shown as a painted three-dimensional *mask*. For color data, a cluster thus defined in color space usually has an ellipsoidal shape, due to a Gaussian distribution of the colors of a particular tissue. This cluster is automatically approximated by a parameterized *ellipsoid*. In general, there are other regions present in the volume which also match this color space description. If they are not connected to the target organ, it can be isolated easily by a 3D connected component analysis. If not, borders are manually sculptured using a volume editor. The result of this procedure is a description of an object in terms of a color ellipsoid or a threshold range and a set of voxels, which are marked by object membership labels.

The volume visualization algorithm we developed is characterized by the fact that it renders surfaces from volume data, using a ray casting approach (6). A decisive quality improvement is achieved by determining the surface positions with subvoxel resolution. This is done by considering first the ellipsoids (or thresholds, for scalar data) and then the object membership labels in the vicinity of a potential surface. Because of the size and resolution of the model, computation of a single image may take several minutes, even on a high-end workstation.

Knowledge Modeling

While segmentation and graphic modeling provide a spatial description of anatomical objects, a comprehensive model also requires a linked symbolic description regarding anatomical terms and their relations. For this purpose, we developed a knowledge base system, using a semantic network approach (3, 7). Among others, an object is described by its names (preferred terms, synonyms, colloquial terms) in various languages, pointers to related medical information (texts, histological images, URLs, etc.), and segmentation and visualization parameters (ellipsoid or threshold values, object label, shading method, etc.).

The knowledge base describes not only elementary parts found in the spatial model (e.g. *left rib 3*), but also compositions of these objects (e.g. *true ribs, ribs, thoracic skeleton, thoracic wall, body wall, body*), thus building a part hierarchy. Furthermore, the knowledge base can represent various “views” commonly used in anatomy. For example, the kidneys can be considered as part of the abdominal viscera (regional anatomy), or as part of the urogenital system (systemic anatomy). Besides the *part of'* relation type, our model also contains other types such as *branching from*, modeling the arterial blood flow.

Intelligent Interactive Scenes

As a major problem, high quality visualization of medical volume models as performed by VOXEL-MAN and similar systems is still too time consuming, and using the program with all its many possibilities and options is often too complicated.

We hence developed a new paradigm allowing to create simpler derivatives of the model, called "intelligent movies" (8). Based on QuickTime VR technology (Apple Computer Inc., Cupertino, CA) intelligent movies allow an interactive exploration of a pre-rendered scene with two degrees of freedom. As a decisive novelty, we extended it by a pixelwise link to the knowledge base which may be queried in the image context. This way, scenes emphasizing a selected aspect of the volume model may be created as intelligent movies, which a user can explore in real time on any standard personal computer.

RESULTS

Using the described methods, we created various spatial and symbolic models of different body parts. The most detailed ones to date represent the torso with the inner organs (7) and the upper limb (9), based on the Visible Human dataset. For these, more than 1000 objects were segmented or modelled and a semantic network with more than 3000 relations was generated by a team of computer scientists, physicians, and doctoral students. Preparation involved up to 10 people and required about 5 man years.

Education in Anatomy

The thus derived models are a versatile interactive tool for reference and education in anatomy. Detailed 3D-anatomy may be viewed from all directions, dissected with any number of cut planes, and structures may be added or removed. As a “self explaining body” they allow to inquire about complex anatomical facts. Visible objects may be interrogated by mouse click. Likewise, objects may be painted to show their extent, or annotated. Vice versa, any object may be painted or annotated using an object list. The system will even find an image where an object is best visible. The capabilities of this application therefore lie between a printed atlas of anatomy and a real anatomical dissection.

As an example of a three-dimensional atlas derived from a model based on the Visible Human data, *VOXEL-MAN 3D-Navigator* contains 19 intelligent movies covering various aspects of the inner organs (10). These pre-calculated scenes provide a real-time performance even on standard computers. Objects may be rotated, removed or added from a list, and the anatomical constituents may be interrogated by mouse click, much like in the original model. Another recently published program, *VH Dissector Pro* (11) provides a model of the whole body with a largely similar functionality.

Because of its complicated anatomy and function, the human hand is a most delicate object for surgery. Therefore a tool for learning the detailed anatomy is of high interest. A 3D model created from the Visible Human dataset is shown in Fig 1.

Simulation of X-Ray Imaging

One of the basic skills of a radiologist is to interpret 3D anatomy from 2D X-ray images. The model allows the simulation of X-rays from any direction and with any beam geometry since the absorption values for every voxel are available from the original CT data (Fig 2). Based on the information contained in the model, both the contributing anatomical structures and the extent of their contribution to the total absorption may be computed and visualized in the context of 3D anatomy.

Simulation of Endoscopy

The problem of understanding images is also evident in endoscopy. Especially for the beginner, it is usually not clear where the endoscope's camera is actually located and where it is looking at. Fortunately, also this procedure can be greatly facilitated by preclinical endoscopy training using a model-based simulation.

Using methods of virtual endoscopy which were originally developed for clinical applications (12), a virtual camera may be moved within the model. The user may interrogate the structures in the viewing area about what is visible on the screen. Position and orientation of the camera may be controlled on 3D views and cross-sectional images (Fig 3).

Simulation of Sonographic Examinations

The situation is even more complicated in endoscopic ultrasonography (EUS) which combines endoscopy and ultrasonography. The idea of EUS is to get as close as possible to the organs of interest by incorporating a small ultrasonic probe into the tip of an endoscope. While visualizing the lumen, the probe can be guided and placed near to the area of interest, thus avoiding bones, adipose tissue, and air filled structures, all of which limit sound wave imaging clarity.

Unfortunately, this sophisticated diagnostic technique is particularly hard to learn. Because of the high flexibility of the endoscope's tip, the scanning plane can be oriented at any oblique angle, making orientation very difficult. Thus, a thorough knowledge of oblique cross-sectional anatomy is mandatory for image interpretation.

Our model based on the Visible Human allows simulation of an ultrasound transducer that may be positioned like in the real procedure (Fig 4). While interactively navigating, the resulting oblique view may be interrogated as to the depicted anatomical constituents, in order to verify whether the chosen position is the desired one. With such a system, cross-sections can be inspected that can not be found in any printed anatomical atlas.

In order to facilitate learning of this procedure, an interactive training system was developed for use on personal computers (13). A set of "intelligent" interactive Quick Time VR scenes allows simulation of a linear-type EUS examination of the gastrointestinal tract while showing the corresponding photographical image sector. With this system, orientation and navigation of an echoendoscope in the gastrointestinal tract can be practiced, as well as the special anatomical knowledge referring to EUS.

To evaluate the suitability of the model for training purposes, real EUS images were compared with the simulations (14). EUS images from individual patients were reported to show excellent correlation with the anatomical model (Fig 4, bottom right).

Training of Surgical Access

For applications in surgery, computer-based anatomy models lend themselves perfectly to interactive lookup of an anatomical situation prior to any intervention. As a step further, recently developed simulation systems allow a realistic rehearsal of medical interventions on a completely virtual basis (15, 16). One example of this kind is the VOXEL-MAN TempoSurg simulator for temporal bone surgery (17, 18).

The objective of temporal bone surgery is to attach implants, to remove tumors, or to perform other treatments of the middle ear. For this purpose, it is necessary to drill through the mastoid bone without hurting several highly delicate organs located in the area, such as facial nerve, auditory ossicles, labyrinth, sigmoid sinus, and dura.

Today, learning to access this complex anatomy is mostly taught by temporal bone drilling of cadaveric material. Since its availability is limited, a virtual reality simulator that enables the student or trainee surgeon to practice different laterobasal surgical approaches is of high value.

As a key innovation, the surgery simulator developed at our institute provides not only a graphical representation of the anatomy, but also a means of manipulation of the data (17) and sense of touch. For this purpose, a “haptic rendering” of the model based on a CT dataset was developed and implemented within our VOXEL-MAN visualization software (18). The trainee interacts with the system via a force feedback device (SensAble Technologies, Inc., Woburn, MA) and sees the scene in stereoscopic display through a mirror (Fig. 5). The simulated procedure becomes thus nearly identical to the real one concerning the patient's orientation as well as the surgeon's viewing direction and hand orientation. The simulator mimics haptic interaction with a realism that comes near to real surgery.

The drill hole looks very much the same as in the real surgical situation. Like in the previous examples, the encountered organs may be interrogated and annotated automatically (Fig 5). Whenever a structure at risk is touched, this is recorded and an optional alarm may be given.

DISCUSSION

In this paper, we presented various applications of three-dimensional models of the human body for education and training in radiology and surgery. For these purposes, the model developed within our VOXEL-MAN project provides the following decisive advantages:

- The developed scheme for anatomical and radiological modelling in terms of spatial and symbolic descriptions leads to an integrated knowledge base allowing exploration and interrogation of the model in a virtually unlimited number of ways.
- Various examinations in radiology and endoscopy and even surgical procedures can be simulated for education and training.
- The model provides a basis not only for graphical, but also for haptic rendering.

Used as a complement to the current curriculum, we believe these models should have a great potential to substantially reduce education times and costs. For example, the surgical simulator allows training with many different normal and pathological cases, which are usually not available in the bone drilling lab. Difficult cases can be repeated many times. Furthermore, since the student is informed whenever he has hit a structure at risk, the system is also suitable for a complementary self-study. However, whether the learning process is really improved remains to be shown. At present, there are two investigations under way by independent research groups for applications in temporal bone surgery and dental surgery, respectively. In both cases, the performance of two groups of future surgeons who are trained with / without the simulator are being compared.

The shown features and applications are only the tip of the iceberg of possible extensions on the way to a comprehensive representation of the human body. First of all, anatomical detail of such 3D atlases is still not sufficient for all needs of radiologists and surgeons. While image data with an even higher spatial resolution are becoming available (19), this is also a problem of computer memory and processing speed; however, with new 64 bit computer architectures, even large models with a spatial resolution well below 1 mm are becoming feasible. The level of detail is thus mostly limited by the effort invested for segmentation.

A more serious problem to be solved is the inclusion of anatomical variability and pathology into the spatial knowledge representation. Modelling of inter-individual variability due to sex, age, race (19) or other factors requires a formal representation of shape which is a currently emerging field (20). To date, most progress has been achieved for 3D atlases of the brain (21), also for the even more difficult representation of pathologies (22). A straightforward, but limited solution to modelling of variability is the collection of different cases.

However, the presented approach should be an excellent basis for further developments. Extension to new application fields such as modelling of acupoints in Traditional Chinese Medicine is currently under way, where such models provide a convenient way to study the relations of such points and the anatomy (23). While today's applications still concentrate on teaching, training, and reference, the knowledge representation will allow features which go far beyond. The model can be easily provided with functional information. Thus, for example, in interventional radiology, the consequences of an embolization at a certain vessel location could be shown by mouse click.

Another important vision for possible future applications of such models is the use for automatic segmentation of image data of an actual patient, going from general to patient specific models. While several man years of work are acceptable for a general model which may be duplicated in arbitrary numbers, it is clear that this is not feasible for clinical cases, such that an automatic segmentation is highly desirable. It is generally agreed that an automatic segmentation requires a spatial description of the human anatomy and its variability (24); furthermore, related problems such as an elastic registration of general and specific models representing different individuals have to be solved. If we succeed, rehearsal of an intervention is no longer based on a more or less arbitrary model, but an accurate digital copy of the patient which exactly represents the particular difficulties of that case. Since this spatial and descriptive information is also available during intra-operative imaging, new functions such as an automatic warning when the surgeon gets near a structure at risk become possible. In conclusion, for advancing Computer Assisted Radiology and Surgery, work on formal representations of the human body should be one of the key areas of research in the future.

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Figures

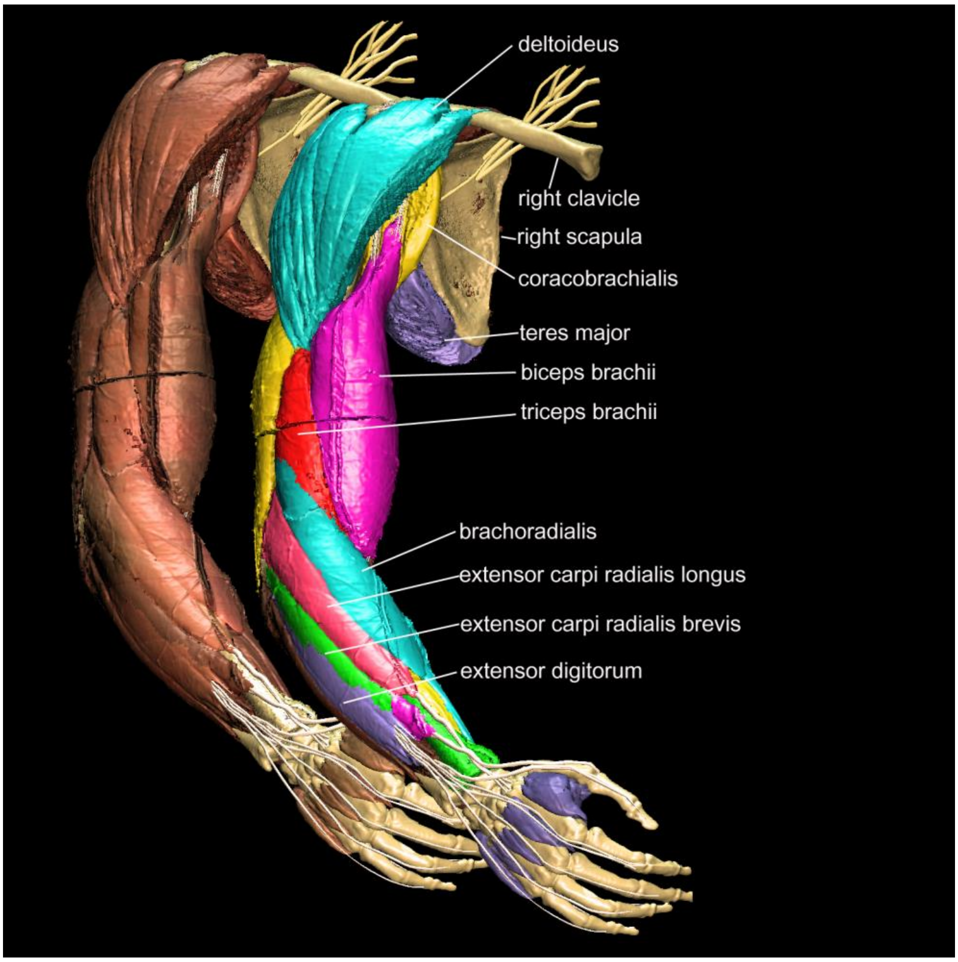

Figure 1. Anatomical model of the arm, based on the Visible Human. Anatomical constituents such as muscles, bones, or nerves may be painted or annotated by mouse click.

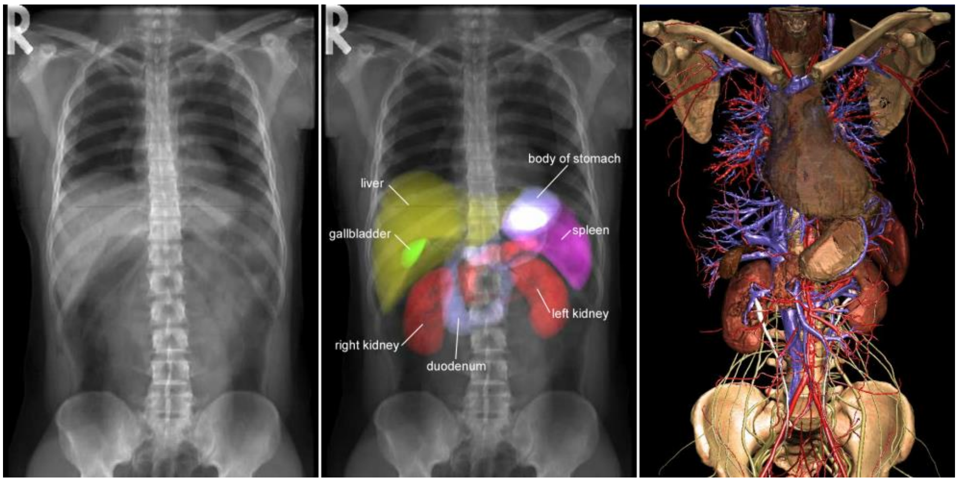

Figure 2. Correlation of x-ray images with 3D anatomy. X-ray images with any beam geometry and from any view direction may be created (left). Interpretation of the images can be veryfied by highlighting the contributions of arbitrary organs (center). Understanding is further improved by corresponding views of the anatomy (right).

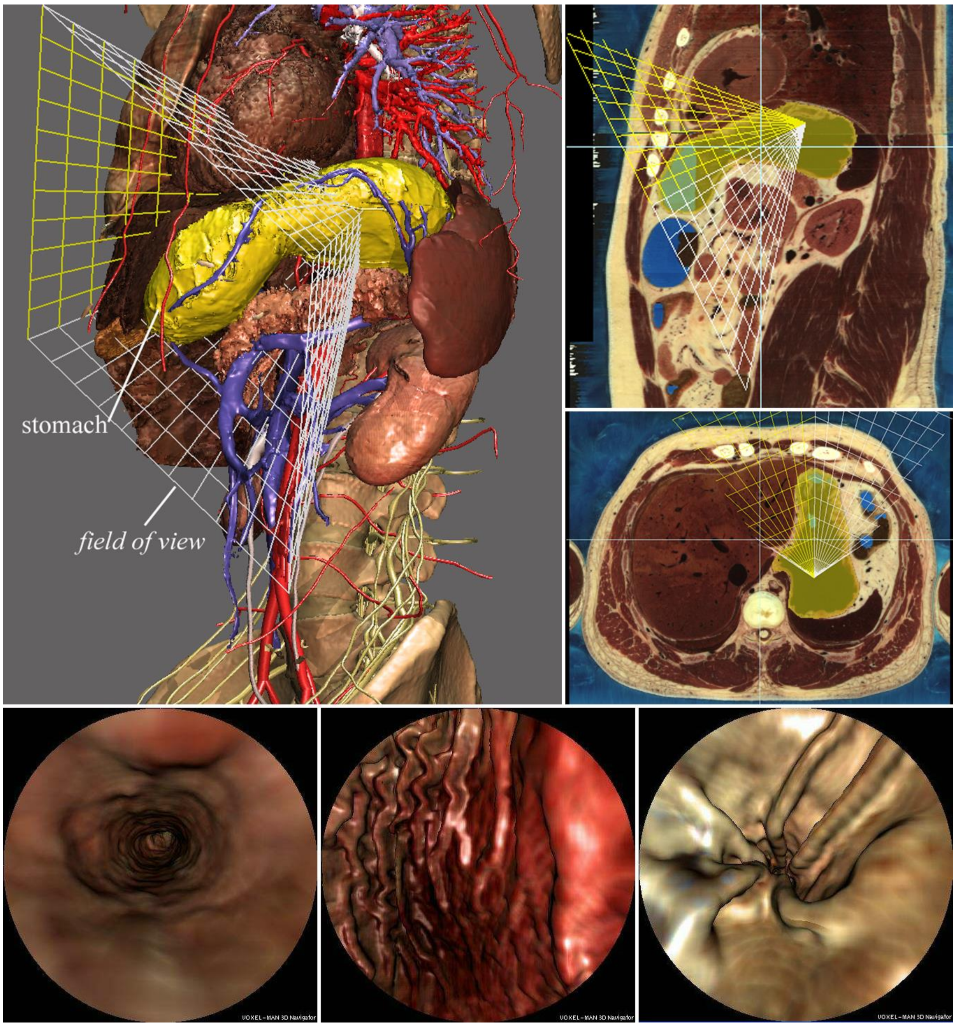

Figure 3. Simulation of gastrointestinal endoscopy. The probe was placed within the stomach, highlighted in yellow. Position and view direction are indicated by the wire mesh, which may be controlled on 3D view (top left) and cross-sectional images (top right). Using this technique, a virtual endoscopy from the esophagus (lower left) through the stomach (lower center) to the pylorus (lower right) may be created. The center image corresponds to the view point defined in the upper images.

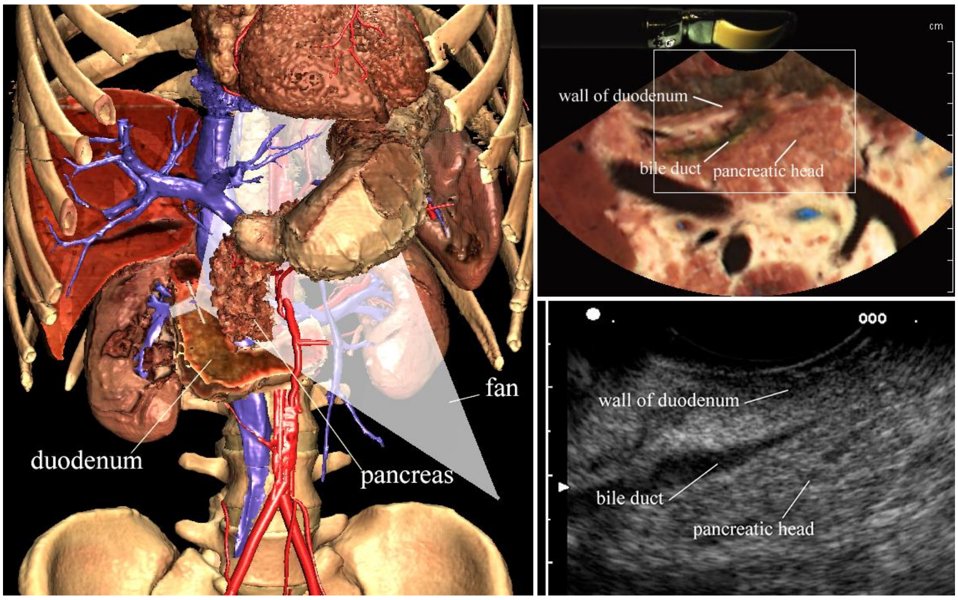

Figure 4. Training system for linear type endoscopic ultrasonography (EUS). The probe (left) is placed in the duodenum, with the view directed to the pancreas. The resulting cross-section (upper right) can be examined and interrogated as to the shown anatomical constituents. The ultrasound image (lower right) shows an analogous view from a patient examination.

Figure 5. Training system for temporal bone surgery. The drilling hole in the mastoid bone created by the student unveils various delicate structures of the inner ear (left). The drill shown in gray is controlled using a force feedback device (right).