Patient-Specific Anatomic Models From Three Dimensional Medical Image Data for Clinical Applications in Surgery and Endoscopy

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Virtual surgery and endoscopy use computer-generated volume renderings and/or models created from 3D medical image scans (CT or MRI) of individual patients. The patient's anatomy, including organs and other internal structures of interest, are then traversed in a virtual "fly-through," giving nearly the same visual impression as if the corresponding real organ was being examined intraoperatively, or as if an actual video or fiberoptic endoscopic procedure was being performed. Such virtual examinations may provide capabilities and information not possible or available in physical examinations. The potential is to provide a noninvasive computer-aided treatment plan or diagnostic screening procedure to augment or replace conventional invasive procedures. With sophisticated image processing and computational analysis, it is possible to perform realistic and useful simulations of surgical and endoscopic procedures, including "virtual dissection and resection" and "virtual biopsy." Surgical margins can be accurately assessed and differential tissue diagnoses made based upon spectral or other information contained in the patient-specific images and models.

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VIRTUAL REALITY (VR) offers the promise of highly interactive, natural control of the visualization process, greatly enhancing the scientific and clinical value of 3D image data produced by medical imaging systems. However, due to the computational and real time update requirements of VR interfaces, the size and complexity of raw 3D medical images cannot be displayed in real time. We have developed efficient methods for the production of accurate polygonal surface representations of anatomic structures computed from patient-specific volumetric image data (such as computed tomography [CT] or magnetic resonance imaging [MRI]). To preserve anatomic detail, we extract sets of intrinsic features from the volumetric image data and use these as input to neural net algorithms, which calculate the surface models. The resulting models capture accurate details of shape, size, and location of the relevant anatomic structures with a minimum number of polygons. The relatively small

number of polygons are optimally distributed over the surface to facilitate real time and faithful display of anatomic structures in virtual environments. The models can be enhanced with textures mapped from photographic or video samples of the actual anatomy and/or with realistic physical and physiological properties (eg, elastic deformations, motion, fluid flow, etc). By using these models on a VR system, we are able to provide realistic and interactive surgery planning and rehearsal capabilities on specific patient data. Applications in neurosurgery planning, prostate surgery planning, craniofacial surgery planning, and myocardial ablation procedures are being developed. Another application of these models is training of anesthesiologists in performing spinal nerve blocks.

Another exciting clinical application of patient-specific models is virtual endoscopy, wherein the models are used to accurately simulate endoscopic procedures, including colonoscopy, esophagoscopy, bronchoscopy, and sinusoscopy. These computed endoscopic procedures offer potential for noninvasive screening for disorders of these anatomic regions. In addition to using polygonal models of patient specific anatomy, efficient perspective volume rendering methods are being developed to produce interactive manipulation and fly-throughs of simulated endoscopy. Several variations of the rendering parameters, including shading, lighting, color, threshold levels, texture mapping, and physical properties can be interactively adjusted to enhance the reality of the virtual simulation. Virtual endoscopy has many potential advantages over real endoscopy. It is noninvasive, eliminating the risk of infection, perforation, and discomfort. Virtual endoscopy allows more degrees of freedom than real endoscopy to explore the

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anatomy; the examination is not constrained by physical or physiological limits. Some measurements that are not possible in real endoscopy can be easily made in virtual endoscopy, including size, distance, shape, and density of selected anatomic structures or regions—in other words a “numerical biopsy.” Endoscopic exploration may be performed simultaneously with external viewing of surrounding anatomy in 3D to provide informative contextual clues. Some patients have physical conditions that may prohibit real endoscopy, making virtual endoscopy a useful alternative. Virtual endoscopy may either replace real endoscopy in some examinations or significantly supplement real endoscopy in others by optimizing performance and minimizing morbidity.

The experience and preliminary results obtained from evaluation of these virtual reality-assisted applications shows significant promise for optimizing certain surgical and endoscopic procedures, minimizing patient risk, morbidity and discomfort, and reducing health care costs.

MODELING ALGORITHMS

The generation of polygonal surfaces occurs in four phases: segmentation, surface detection, feature extraction, and polygonization. We initially segment the volumetric data into the objects of interest using the tools found in ANALYZE and A Visualization Workshop (AVW).¹ Segmentation consists of a series of three-dimensional mathematical morphological and/or multispectral classification operations that will extract objects from an image data set with a minimum of user interaction. These objects are then presented to surface detection and feature extraction (eg, curvature) algorithms, and the resulting images form the input for the polygonization algorithms.

To tile a surface, an initial surface is generated, typically a cylinder, consisting of a specified number of quadrilateral polygons encompassing the bounding box of the object. The 3D coordinates of the polygonal vertices are used as the initial position vectors for the nodes of a 2D Kohonen network.² The network has as many nodes (units) as there are polygonal vertices and is a rectangular lattice with a cylindrical topology. The network is then allowed to adapt to the segmented surface, using those voxels with a nonzero curvature weighting as the set of sample vectors to drive the mapping of the polygons.

Another tiling algorithm is based on the “growing cell structures” of Fritzke³ and involves successive addition of new nodes to an initially small 2D Kohonen network by evaluating local statistical measures gathered during previous adaptation steps. The network is adapted to a set of sample vectors by a Competitive Hebbian Learning (CHL) model, which involves the addition of new edges, or connections, to the network. With this “Growing Net” algorithm, only a relatively small number of polygons (usually 1,500 to 2,500) is required to produce an accurate and useful 3D representation of complex anatomic structures.

RESULTS

The example applications presented here are meant to be exemplary, not exclusive. They illustrate the use of 3D biomedical images and patient-specific models in support of specific clinical goals and are current works in progress.

Surgery Rehearsal

We are developing a system called the Virtual Reality Assisted Surgery Program (VRASP)⁴ for implementation into the hospital operating room (OR). VRASP is intended to provide support for preoperative planning and rehearsal, but also on-line access to the preoperative data during the surgical procedure in the OR, and real time qualitative and quantitative comparison between OR data and the preoperative plan. The project is designed in three phases: (1) surgery planning, (2) surgery rehearsal, and (3) surgery deployment. VRASP will include important new tools for efficient polygonization of volumetric data as described in this report. Due to hardware-dependent limitations on the number of polygons that may be rendered in real time, algorithms to generate polygonal surfaces with a specified polygonal budget from a volumetric data set are ideal, allowing for patient-specific anatomic geometric models to be computed from patient scan data.

Figure 1 is a posterior oblique view of a model of the pelvic girdle determined from a 3D CT scan and models of the bladder, prostate, and other adjacent structures, including a tumor, determined from a 3D MRI scan. The CT and MRI scans were coregistered to accurately combine the pelvic bone from the CT with the soft tissue organs from MRI.

Urologic surgeons are enthusiastic about using these models, as they allow the surgeon to critically

Fig 1. Right posterior oblique view of model of pelvis fused with patient specific models of prostate and adjacent anatomy. These models can be interactively visualized and manipulated in accurate 3D context. The icon in the upper right dynamically indicates full body orientation.

study the anatomic relationships in a real time virtual environment preoperatively. Figure 2 shows detailed models of a normal prostate (top, center) and two patients (lower left and lower right). The patient-specific models can be studied independently, outside the framework of the pelvic model, or with the patient's pelvic girdle in place, provided the necessary CT data is available.

Three-dimensional visualization and manipulation of models of patient-specific brain anatomy are being used for neurosurgical planning and rehearsal using virtual reality technology. Figure 3 illustrates texture-mapped models of a patient brain and segmented ventricles, including two frames from an endoscopic fly-through of the ventricles. The very complex shape of the cerebral cortex and ventricles is accurately captured with only 25,000

Fig 2. Several models of the prostate gland and adjacent anatomy computed from MRI scans of a normal patient (top) and two actual prostate cancer patients (bottom). Bright (red) regions are tumors in the lower prostate models.

Fig 3. Texture-mapped models of patient brain and ventricular system computed from 3D MRI scan. Top shows texture-mapped surface and transparency. Bottom shows internal views of ventricles. Models faithfully capture the shapes of these complex structures, providing useful preoperative visualization for surgery planning.

total polygons using our algorithms. These models are accurate in size, shape, and location, and therefore useful to surgeons for preoperative planning of brain surgery.

Computed Endoscopy

Computed or virtual endoscopy is a term used to describe a new method of diagnosis using computed processing of 3D medical data sets (such as CT or MRI scans) to provide simulated visualizations of patient-specific organs similar or equivalent to those produced by standard endoscopic procedures.⁵⁻⁷ Thousands of these standard endoscopic procedures are performed each year. They are invasive and often uncomfortable for patients. They sometimes have serious side effects such as perforation, infection, and hemorrhage. Computed endoscopic visualization avoids the risks associated with real endoscopy and when used before performing an actual endoscopic exam can minimize procedural difficulties and decrease the rate of morbidity, especially for endoscopists in training. Eventually, when refined, computed endoscopy may replace many forms of real endoscopy.

As 3D medical imaging and computer power improve, virtual representations of anatomic and physiologic data will become increasingly realistic and interactive, significantly advancing the science of computed noninvasive endoscopic examination. However, there remains a critical need to refine and validate these simulations for routine clinical use, and the Visible Human Dataset (VHD) from the National Library of Medicine⁸ is ideally suited for this. We have used the VHD to develop, test, and

compared 3D visualization and image processing methods and to evaluate the effectiveness of these methods, including endoscopic simulation, for eventual applications in clinical diagnosis and therapy.

At the center of Figure 4 is shown a transparent rendering of a torso model of the VHM containing some of these segmentations. This particular torso model has been used to develop and evaluate computed endoscopic procedures applied to a variety of intraparenchymal regions of the body. Surrounding the torso in Figure 4 are several computed endoscopic views, which are single frames captured from fly through sequences of the stomach, colon, spine, esophagus, airway, and aorta of the VHM. Also illustrated in the simulated endoscopic views are different types of navigational guides superimposed on the display to help the user interactively determine body orientation and precise anatomic localization while performing the computed endoscopic examination.

Figure 5 illustrates volume renderings of segmented anatomic structures from a spiral CT scan of a patient with colon cancer and polyps. The upper left image is a transparent rendering of a portion of the large intestine selected for segmentation and the rather large circumferential rectal cancer at its distal extent. The upper right and lower left images show these same anatomic segmentations at different angles of view with the skin removed. The lower right panel shows a volume rendering of the isolated colon and cancer from a posterior oblique view with magnified section, a

Fig 4. Virtual endoscopic views inside various segmented organs of the Visible Human Male from the National Library of Medicine. Views include stomach, colon, spinal column, esophagus, trachea, and arch of aorta near heart. Small icons superimposed on each endoscopic view indicate full body orientation, 3D location, and 2D position.

Fig 5. Volume renderings of anatomic structures segmented from a spiral CT scan of a patient with colon cancer. Top panels show oblique anterior view with transparency and skin removed. Bottom left panel shows posterior view and bottom right shows a midsigmoidal polyp (blue) in the oblique posterior view of the isolated bowel.

midsigmoidal polyp (blue) is also identified, segmented, and rendered in this view.

Because of the position and extent of the tumor in this case, it was not possible to examine the midsigmoidal polyp using standard endoscopic techniques. However, as illustrated in Figure 6 we were able to digitally analyze the polyp in a number

Fig 6. Virtual biopsy of polyp. Top left shows close-up view; top right shows enhancement of polyp surface; bottom left shows transparency indicating high intensity region (probably vascular); bottom right shows measurement of polyp diameter and volume.

of ways using virtual endoscopy. The upper left panel is a texture mapped computed endoscopic view of the polyp at close range, while the upper right shows an enhancement of the polyp against the luminal wall. Such enhancement is possible only with computed endoscopy, as the polyp itself can be digitally segmented and processed (eg, brightened) as a separate object. The lower left panel is a transparent rendering of the polyp, showing a dense interior region, which was also segmented. This is most likely a denser than normal vascular bed, perhaps a precursor of malignancy. The lower right panel illustrates the capability for "virtual biopsy." Both geometric and densitometric measures may be obtained numerically from the segmented polyp (density measures can be computed from the original image data).

SUMMARY

We have presented methods for the production of efficient 3D geometric (polygonal) surfaces containing a prespecified number of polygons from volu-

metric medical image data. We have determined that these surfaces are efficient as they accurately reflect size, shape, and position of the modeled objects and are built from a specified number of polygons, selected to optimize the trade-off between surface detail and real time display rates. These efficient models can be used in various medical applications such as computed endoscopy, surgery planning and rehearsal, and as a powerful educational tool for teaching anatomy.

We believe that efficient creation of anatomic models from patient specific image data, together with their application in computed endoscopy and surgery rehearsal, will contribute to significant improvements in health care delivery, including better surgical outcome, reduced morbidity, and lower costs.

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