Virtual Endoscopy: Application of 3D Visualization to Medical Diagnosis

Abstract

Virtual endoscopy is a diagnostic technique in which a three-dimensional imaging technology (CT scan, MRI scan, ultrasound) is used to create a computer-generated representation of a specific patient’s anatomy or organ, and then the virtual organ is “flown through,” giving the same visual impression and image as if the corresponding real organ had a video or fiberoptic endoscopic procedure performed. The potential is to provide a computer diagnosis to replace an endoscopic procedure, not only for conventional endoscopy such as bronchoscopy, colonoscopy, sinusoscopy, or hysteroscopy, but also for areas where traditional endoscopy is not possible, such as the inner ear, spleen, lymphatic tissues. With sophisticated signal processing and computational analysis, it may be possible in the future to perform a “numerical biopsy,” that is, make a tissue diagnosis based upon spectral or other information contained in the images.

I Introduction

Virtual endoscopy (or computed endoscopy) is a term used to describe a new method of diagnosis using computer processing of 3D image datasets (such as CT or MRI scans) to provide simulated visualizations (Geiger and Kikinis, 1994; Rubin et al., 1996) of patient specific organs similar or equivalent to those produced by standard minimally invasive endoscopic procedures (Wickham, 1994). Examples of current endoscopic procedures include bronchoscopy, sinusoscopy, upper GI endoscopy, colonoscopy, cystoscopy and ureteroscopy, hysteroscopy, and arthroscopy. Thousands of these procedures are performed each year. These procedures are invasive and often uncomfortable for patients. They sometimes have serious side effects such as perforation, infection, and hemorrhage.

Conventional CT and MRI scans produce cross section “slices” of the body that are viewed sequentially by radiologists who must imagine or extrapolate from these views what the actual three-dimensional anatomy should be. By using sophisticated algorithms and high-performance computing, these cross sections may be rendered as direct 3D representations of human anatomy. Specific anatomic data appropriate for realistic endoscopic simulations can be obtained from 3D MRI digital imaging examinations (Rusinek et al., 1989) or 3D acquired spiral CT data (Napel, 1995).

Virtual endoscopic visualization of patient-specific anatomic structures avoids the risks associated with real endoscopy, or can provide the endoscopist with important anatomic information prior to performing an actual endoscopic
exam. Such understanding can minimize procedural difficulties and decrease the rate of morbidity, especially for endoscopists in training. Eventually, when refined, virtual endoscopy may replace many forms of real endoscopy. Although virtual endoscopy does not allow direct physical biopsy or treatment options, it may potentially be used in screening diagnostic examinations with the advantages of reduced cost, less discomfort, and lower risk. In addition, accurate, realistic simulations can be performed for teaching endoscopic techniques and for periodic practice of procedures performed infrequently. There has been speculation about such capabilities since the 1970s, as dramatized in the movie “Fantastic Voyage,” but the recent ability to accurately and rapidly render medical images in three dimensions and to perform fly-throughs instead of inserting long instruments (endoscopes of any kind) into a patient now represents the modern Information Age realization of this voyage, and it is fantastic.

Advanced approaches to visualization of specific anatomical models in support of endoscopic training, rehearsal, or diagnosis can be implemented on a virtual reality display system (Robb and Cameron, 1995; Merril et al., 1994; Satava, 1995). Such displays are “immersive,” and allow the endoscopist to simultaneously visualize the anatomy and manipulate the viewing orientation in a realistic way (Fischer, Neisius, and Trapp, 1995; Frolich et al., 1995). In fact, virtual endoscopy provides viewing control and options that are not possible with real endoscopy, such as direction and angle of view, scale of view, immediate translocation to new views, lighting, and measurement. Visual feedback positioning systems and navigation guides can orient the virtual endoscopist relative to the actual anatomy. Image values from the original data can be associated with any view and quantitatively assessed. Simulated views can be compared to actual endoscopic images and postoperative pathologic data to validate their usefulness.

There are many body regions not accessible to real endoscopy that can be explored with virtual endoscopy. A few of these could potentially be explored with miniaturized endoscopes, but they are currently unavailable. Several important body systems are not compatible with invasive probes. Regions such as the heart, spinal canal, inner ear (cochlea, semicircular canals, and so on), biliary and pancreatic ducts, and large blood vessels are important anatomic structures ideally suited for virtual endoscopy. For example, a virtual representation of a patient’s inner ear computed from high resolution 3D images would permit the virtual physician to scale down to millimeter size within the semicircular canals, perform a diagnostic fly-through, simulate a surgical procedure, do preoperative planning, fuse the image during stereotactic surgery, and predict alternative outcomes based upon the procedure performed. This is the power and promise of virtual endoscopy applied to a single, patient-specific 3D image volume data set.

2 Background

The history of virtual endoscopy is a brief one. It is a very recent technology in diagnostic medical imaging. Virtual endoscopy derives principally from digital medical imaging, and in particular from visualization of 3D CT and MRI data sets. However there are roots in nonmedical areas of 3D visualization, including computer science, terrain guidance, flight path planning, and flight simulation (Holloway, Fuchs, and Robinette, 1992; Kaltenborn and Reinhoff, 1993). The fundamental concept common to all of these efforts is the representation of real-world objects (such as patient organs and tissues) as spatial information. For digital medical image information, the spectrum of physical and computer science methods available to acquire, process, analyze, convert, scale, enhance, fuse, distribute, and transmit information can be applied in ways that permit diagnostic and therapeutic capabilities beyond current human physical abilities and possibilities.

A number of investigators have been working in this field. Some of the earliest work was published by the following: Vining (Vining and Gelfand, 1994; Vining et al., 1994) on virtual colonoscopy; Lorensen (Lorensen, Jolesz, and Kikinis, 1995), who performed 3D fly-throughs of carotid arteries and A-V malformations; Robb (Robb and Cameron, 1995; Robb and Barillot, 1989; Robb and Hanson, 1993), who began with patient-specific 3D organ visualizations and progressed to
interactive organ fly-throughs; Hara and Johnson (Hara et al., 1996), who have published early clinical observations in the colon; Jolesz and Kikinis (Jolesz and Shtern, 1992; Kikinis, Langham Gleason, and Jolesz, 1995), who developed “enhanced reality” using 3D visualization and image fusion for stereotactic neurosurgery; and Napel and colleagues (Rubin et al., 1996; Napel et al., 1996), who have applied simulated endoscopy to a variety of intraparenchymal visualizations. As 3D medical imaging and computer power improved, these early pioneers appreciated the power and promise of virtual representations for realistic visualization and manipulation to advance the science of noninvasive endoscopic diagnosis.

3 Methods

One general schema for producing virtual endoscopy procedures is diagrammed in Figure 1. Three-dimensional images are first acquired from a scanner (e.g., spiral CT, MRI, confocal microscopy). Invariably, some preliminary processing on this data is required to properly prepare it for modeling. This pre-processing step may include interpolation to transform the data set into isotropic elements, registration to bring all images into spatial synchrony, and segmentation to reduce the data set to the desired specific anatomic structure(s). Many approaches to model creation have been proposed (Cameron, Manduca, and Robb, 1996; Gueziec and Dean, 1994; Hoppe, 1994; Karron, Cox, and Mishra, 1994; Thalmann and Thalmann, 1994; McMillan and Bishop, 1995; Rosen, 1992), but generally single anatomic objects must first be segmented from the 3D images and their surfaces extracted. The isolated surface is then converted to a geometric representation, a process referred to as tiling, by transforming surface coordinates to a meshwork of polygons (Cameron, Manduca, and Robb, 1996; Gueziec and Dean, 1994; Hoppe, 1994; Karron, Cox, and Mishra, 1994). The polygonal surface representation may then have appearance-modifying information added to it, such as color, lighting, textural patterns. This processed data set comprises the model, which then may be rendered for visualization using a surface or volume-rendering algorithm, of which there are many available (Robb and Barillot, 1989; Lorensen and Cline, 1987; Dreibin, Carpenter, and Harrah, 1988; Hohne et al., 1990; Levoy, 1988). The user or operator previews the rendering and accepts it as faithful and/or useful, or the user can choose to repeat some phase of the process (e.g., segmentation and/or surface definition) to obtain an acceptable model for rendering. This iteration and acceptance decision is generally made by a human expert (e.g., radiologist, surgeon, endoscopist). The endoscopic display procedure is then simu-

![Figure 1. Diagram of general procedure for virtual endoscopy using geometric modeling.](http://www.mitpressjournals.org/doi/pdf/10.1162/pres.1997.6.2.179)
lated in one of two ways: (1) online, real-time display using an interactive simulator, such as a virtual reality display system (Robb and Cameron, 1995; Satava, 1995) with rapid computational capabilities that can produce updated displays at real-time rates in response to user interactions (e.g., using a head-mounted display, or head-tracking and 3D input devices); or (2) a predetermined “flight path” is used to compute sequential frames of views that are rendered in an animated video sequence. There are variants to this overall process, but this description is generally representative of current methods for virtual endoscopy.

One of the notable variants of the method diagramed in Figure 1 is shown in Figure 2. In this approach to virtual endoscopy, a model is not generated, but rather the appropriately segmented images are rendered directly using volume rendering with perspective (Rubin et al., 1996; Robb and Barillot, 1989; Napel et al., 1996). This is a well-known ray-casting approach (Drebin, Carpenter, and Harrahan, 1988) that generates various surface views using a specified set of conditions and/or constraints on the rendering process as rays are passed mathematically through the voxels of the 3D image. Since this is a computationally intense procedure, even the fastest of modern workstations cannot render full visualizations of large images at real-time rates. However, the problem appears to be solvable with continuing advances in computer technology. Therefore, similar to the offline option of modeling approaches, predetermined flight paths and animation are performed to produce cine sequences that can be viewed subsequently at video frame rates. In contrast to modeling, there is a potential power in perspective volume rendering, especially when computational rates become less prohibitive for large datasets. That power lies in the intrinsic 3D richness of the volume data that is preserved. Depth layers may hold subtle but important information to enhance the usefulness of the visualization, such as blood vessels in the luminal wall, fine trabeculations, subdural lesions, etc. Such detail is not likely to be captured in surface models.

Figure 3. Transparent volume rendering of anatomic models of several organs in torso of NLM visible human male. (Data courtesy of National Library of Medicine, National Institutes of Health.)
Figure 4. Virtual endoscopic views of two different segments of stomach of visible human male captured from real-time fly-through of stomach, with various navigational guides superimposed upon field of view.
The user interface to a virtual endoscopy system varies depending on the display mode. In real-time simulations (Robb and Cameron, 1995; Fischer, Neisius, and Trapp, 1995; Frohlich et al., 1995; Holloway, Fuchs, and Robinette, 1992; Jolesz and Shtern, 1992; Satava, 1995) the user wears a head-mounted display or special stereo glasses and manipulates the 3D image with various feedback and 3D input devices. This interface is immersive and responsive online, and places the user inside the visualization domain (vis-a-vis “Fantastic Voyage”). In cine or video path tracking, the interface is generally a computer workstation screen and pointing device that the user employs outside of the visualization domain to control replay of predetermined fly-throughs. These displays can also be rendered and replayed on video tape, CD-Roms or other multimedia devices.

4 Evaluation

The visible human male (VHM) data set from the National Library of Medicine (National Library of Medicine [US] Board of Reagents) is being used by an ever-increasing number of investigators to develop, test, and compare 3D visualization methods for evaluation of eventual applications in clinical diagnosis and therapy. These methods include the algorithms for segmentation, modeling, and rendering that are used in virtual endoscopy. The Biomedical Imaging Resource at Mayo Clinic was one of the first labs to receive this unique, high-resolution image data set, and has been engaged in accurately segmenting and modeling the major anatomical structures of the VHM for several months (Robb and Cameron, 1995; Cameron, Manduca, and Robb, 1996). Figure 3 shows a transparent rendering of the torso of the VHM obtained from some of these segmentations and models. This particular torso model has been used to develop and evaluate virtual endoscopic procedures.

Figure 4 shows two different virtual endoscopy views captured from a fly-through of the segmented and modeled stomach of the VHM. These visualizations illustrate the surface detail that can be visualized with virtual endoscopy. (The procedure used is similar to that described in Figure 1.) Figure 4 also illustrates three different navigation guides superimposed upon the display to help the user interactively determine body orientation and precise anatomical localization while performing the virtual endoscopic examination. The icon at the upper right dynamically updates body position relative to current eye viewing position; the transparent thumbnail of the model at upper left shows a bright dot at the 3D location of the current view; and the CT section at lower left is perpendicular to the current viewpoint, with a bright dot showing the current projected anatomic location of the virtual endoscopic probe.

Figure 5 shows four panels of virtual endoscopy views captured at selected locations during fly-throughs of the VHM trachea (upper left), esophagus (upper right), colon (lower left), and aorta (lower right). The view from within the aorta shows the junction of the innominate, left common carotid, and left subclavian arteries. Such visualizations are not possible with real endoscopy. The virtual visualizations of the trachea, esophagus, and colon have been compared with real endoscopic views by endoscopists who judge them to be realistic and useful.

Figure 6 is yet a different virtual endoscopy visualization of the colon of the VHM. Four perspective volume renderings illustrate views at four different locations,
Figure 6. Perspective volume rendering within colon of visible human male showing different viewpoints of different segments illustrating luminal surface detail. Upper panels show slight change in angle of view of same segment; lower panels show views of entirely different segments.

demonstrating the capability of virtual endoscopy for rapid translocation of viewpoint, and also revealing the richness of texture (detail) on the segmented surface. Since these renderings are performed from the original volume image data, not computed models, more detailed anatomic structures are visible in the images. Such renderings also exhibit modest layering patterns corresponding to the separation between imaged slices in the original CT scan data. Fly-throughs using such views can be produced by computing successive view frames along a predetermined flight path through any segment of the colon.
Figure 7. Processing of spiral CT scan data of patient with esophageal cancer in preparation for virtual endoscopy. Upper-right panel shows volume rendering of segmented objects (skin, lungs, trachea, esophagus, stomach, cancer) and location of four selected CT cross-sections shown numbered at upper left. Lower panels show successive removal of anatomic structures to isolate the esophagus and cancer. Note that the cancer severely constricts the esophagus, precluding segmentation of its connection to the stomach. (Scan data courtesy of Dr. Charlene Prather, Mayo Foundation.)

Quantitative measurements of geometric and densitometric information contained in these models and the correlated image data can be carried out. Preliminary studies and analyses (Laurent et al., 1994) are providing growing evidence of the potential of virtual endoscopy for accurate and reproducible visualizations.

5 Some Clinical Applications

Although virtual endoscopy is in the embryonic evaluation stages in clinical practice, descriptions of methods and preliminary results are increasing in scientific meetings, workshops, and publications (Rubin et
al., 1996; Robb and Cameron, 1995; Vining and Gel- 
fand, 1994; Lorensen, Jolesz, and Kikinis, 1995; Robb 
and Hanson, 1993; Hara et al., 1996; Jones and Satava, 
1996; Peifer, Curtis, and Sinclair, 1996; Preminger et 
al., 1996; Silverman et al., 1992; Ramaswamy and Hig- 
gins, 1996; Davis et al., 1996; Kimura et al., 1996). Re- 
ported here are two typical clinical examples of virtual 
endoscopy—one in esophageal cancer and one in colon 
cancer.

Figure 7 illustrates a sequence of image processing in 
preparation for a virtual endoscopy exam of the esophag- 
us. The upper-left panel in Figure 7 shows four cross-
sections through the chest from a spiral CT scan of an 
esophageal cancer patient. The cancer, which constricts 
and almost completely occludes the esophagus, can be 
seen in section number 3. The upper-right panel is a 
transparent volume rendering of several segmented ana-
tomic structures from this scan, including the skin, 
lungs, trachea, esophagus, cancer, and part of the stom-
ach. The location of the selected cross-sections are indi-
cated by the dashed lines. The lower two panels illustrate 
renderings with some objects removed. In the lower-
right panel, the esophagus is seen to be squeezed off by 
the circumferential constricting cancer, making it impos-
sible to segment the distal portion adjoining the stomach.

Figure 8 illustrates four virtual endoscopy views of this patient’s esophagus, computed from the segmented esophagus shown in Figure 7. The upper-left panel shows a segment of normal esophagus near level 1. The upper-right panel is a view just above the pronounced narrowing in the esophagus near level 2. The lower-left panel is yet a more distal view just above level 3, which reveals an infiltrating portion of the cancer. The lower-right panel is the same view as the lower left, but the esophageal wall has been rendered transparent to reveal the entire lesion wrapped around the esophagus. Such global views of the cancer are impossible with real endoscopy.

Figure 9 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 bowel selected for segmentation and of the rather large circumferential rectal cancer at its distal extent. The upper-right and lower-left images reveal these same anatomic segmentations at different angles of view with the skin removed. The lower-right panel shows a volume rendering of the isolated large colon and cancer from a posterior oblique view. Also identified, segmented and rendered in this image is a polyp (blue) in the midsigmoid region.

Figure 10 shows a close-up virtual endoscopy view (bottom) of this polyp (arrow) compared with a real endoscopic view (top) of a colon polyp from another patient. Although this figure does not provide a comparison of the same polyp, the relative quality of real and virtual endoscopy of the colon can be subjectively evaluated from such comparisons. The texture of the image in the real endoscopic view has been sampled and mapped (Cameron, Manduca, and Robb, 1996) onto the virtual colon image to enhance the realism of the simulation.

Figure 11 shows different ways of digitally analyzing the patient polyp with virtual endoscopy. The upper-left panel is a texture-mapped virtual endoscopy view of the polyp at close range, and the upper-right panel shows an enhanced visualization of the polyp against the luminal wall. Such enhancement is possible only with virtual endoscopy, since the polyp itself can be digitally segmented and processed as a separate object. The lower-left panel is a transparent rendering of the polyp, revealing a dense interior region that was also segmented. This rendering shows what is most likely a denser-than-normal vascular bed (perhaps a precursor of malignancy). The lower-right panel illustrates a capability unique to virtual endoscopy—“virtual biopsy.” Both geometric and densitometric measures may be obtained numerically from the segmented polyp.

Figure 12 illustrates two other forms of displaying the luminal wall of the colon and the polyp. The top two panels are radial volume renderings (Robb and Hanson, 1993) of the segmented colon image data, wherein the image volume segment containing the polyp is splayed open like a mercator projection in order to get a flat slab

Figure 9. Volume renderings of anatomic structures segmented from spiral CT scan of patient with colon cancer. Upper images show transparency and skin removed to reveal sections of bowel selected for segmentation, as well as circumferential rectal cancer (red). Lower images show rotated views. A midsigmoid polyp (blue) can be seen in the oblique posterior view of the isolated bowel at lower right. (Scan data courtesy of Dr. Michael Vannier, Washington University.)
Figure 10. Top is actual video frame from a standard real endoscopic examination of the colon of a patient with a polyp (arrow). Bottom is a selected frame from virtual endoscopic fly-through of patient colon, showing the midsigmoid polyp (arrow) segmented in Figure 9. Although these are different patient data sets, the comparison provides an appreciation for the relative fidelity of virtual endoscopic imaging. The texture from the real endoscopic image has been mapped onto the model used for the virtual endoscopic image.
view of the entire surface. A dissecting wedge into the wall (upper right) reveals the location and extent of penetration of the polyp (blue) into the luminal wall. The lower two panels in Figure 12 are “clam-shell” views of the model of this same colon segment containing the polyp. As the wall is “unzipped” and swung open, the luminal wall and polyp can be clearly seen.

6 Some Current Problems

The visual fidelity of current generation virtual endoscopy images is not yet at the level of diagnostic accuracy suitable for regular clinical diagnostic use. There are a number of technical problems that have to be solved to make virtual endoscopy a clinical tool with sufficient scientific validity and ease of use to be employed on a routine basis. These include: (1) 3D image resolution, (2) accurate surface rendering, (3) automatic segmentation, (4) robust registration, and (5) appropriate preparation.

Current 3D images from CT and MRI scans readily demonstrate resolving power to 5 mm, and some labora-
tory results on phantoms are demonstrating images of lesions with 1 and 2 mm accuracy (Silverman et al., 1992; Ramaswamy and Higgins, 1996; Davis et al., 1996; Kimura et al., 1996). The current generation of helical or spiral CT scanners are capable of 1 mm resolution (Napel et al., 1996), but this is not used routinely. As scanner resolution improves to the submillimeter level, the resolution of virtual endoscopy will also improve. Current scanning resolution can be used for screening procedures of clinically relevant lesions in the colon, but improvements to at least the 1 mm level are required to support a broad spectrum of use. Higher 3D resolution will provide the requisite structural and anatomical detail for clinical use of virtual endoscopy; however, surface textures comparable to those in the optical image obtained from standard endoscopy still require significant improvement. Surface rendering uses a variety of shading techniques and/or application of generic texture mappings related to the specific organ (Cameron, Manduca, and Robb, 1996; Thalmann and Thalmann, 1994); therefore, surface (e.g., mucosal) details in such renderings are only a form of mimicry. Since these are not patient specific, they are not helpful for diagnostic purposes. Diagnoses based upon anatomic deformities by mass lesions (polyp, cancer, cyst, edema from inflammation, ulcer, stricture, and so on) can be made, but other lesions that are diagnosed by subtle mucosal changes (such as inflammation, superficial ulcers, vascular ectasia) cannot be faithfully represented by current virtual endoscopy methods.

Achieving accurate, reproducible, automatic organ or tissue segmentation remains a significant challenge. Segmentation is an essential step to permit individual organs to be distinguished from one another. Currently, segmentation is most often done by “post-production” techniques—after the full image data set is acquired, the data is either meticulously segmented manually (drawn or identified by hand) or by various semiautomatic algorithms. Some promising progress is being realized toward fully automated 3D segmentations of both hard tissue (bone) and soft tissue (such as skin and muscles) (Robb and Hanson, 1993). What is ultimately desirable is for the image to be automatically segmented “on the
Figure 12. Top row: Radial cylindrical (splaying) volume rendering of segment of colon containing polyp, with dissection (upper right) into polyp to reveal its penetration into the luminal wall. Bottom row: "clam-shell" views of model of colon segment containing polyp, showing two frames of dynamic sequence of "unzipping" the wall and opening it to reveal the polyp.

fly" as it is being acquired, and then be immediately usable as the fully segmented organ with or without a series of cross-sectional or multiple orthogonal views. Until this occurs, capabilities for routine visualization of 3D image data sets as virtual organs and tissue will be available at only a few centers with sufficient resources to effectively process the images.

Like segmentation, solutions to the problem of automatic, frameless registration between two or more images is needed for routine clinical implementation of these visualization methods. Currently, fiducial markers are required for proper acquisition and alignment (fusion) of images from different imaging sources such as CT or MRI, or from video and CT. Although align-
ment and fusion can be routinely accomplished with static images, the application to dynamic images that might be obtained during surgery is limited to a few selected applications, such as stereotactic neurosurgery. In order to extend the utilization to a broader field of procedures, robust solutions will need to be developed for online dynamic acquisition (Blumenfeld, 1996) and fusion of in vivo organs and tissues that change in shape and position.

Some organs or tissues require special preparation in order to be properly visualized. Gastrointestinal structures such as the colon need to be “prepped” with various regimes to remove feces that interfere with segmentation and interpretation. Under most circumstances, blood vessels require injections of contrast material to enhance their visualization using medical imaging scanners. While some traditional preparatory methods might be effective, other newer techniques will be needed to provide a level of visualization adequate for routine clinical implementation.

### 7 Summary and Speculation

There is a broad range of potential applications of the segmented virtual patient, of which virtual endoscopy is an integral part. For example, once the image data is acquired and visualized, it can be used (1) for diagnosis as a virtual gross anatomic (or pathologic) specimen; (2) it can function as a virtual endoscopy model for preoperative planning of a specific complicated surgical (or radiotherapy) procedure; (3) it can be practiced upon as a surgical (or catheter-based or radiotherapy) procedure simulator; and (3) in certain cases, it can be used as a prognostic planner.

In order to illustrate the current state of the art relative to what appears to be a useful clinical goal for a virtual patient, Table 1 classifies the evolutionary types or generations of medical procedure simulation using virtual environments for applications based on all levels of gross, microscopic, and physiologic representation.

Each succeeding generation is more complex, integrates the preceding generation, and follows a chronological development based upon technical limitations of the time period. The ultimate goal is to produce a virtual photorealistic human that has complete physical, physiologic, and systemic fidelity. Initially, 3D geometric anatomic shapes were computed, with some simple interactivity (generation 1). This generation of achievement permitted identification of gross anatomic structures, simple fly-throughs, and very crude manipulation of cartoon-like organs, such as gall bladder and liver.

Computer power rapidly increased to user in generation 2, which had more realistic graphics, included physical properties of tissue such as stretching and deformation (plasticity), and allowed interactive positioning of anatomic structures. Interactive simulations (such as deform, cut, divide) could be performed on any portion of the virtual organ.

There are a few virtual representations that are beginning to incorporate generation 3, which includes rendering physiologic properties such as breathing, bleeding, leaking of bile or urine, and motility in highly realistic ways. Generation 3 has utilized either the Visible Human (National Library of Medicine [US] Board of Reagents) or patient-specific data derived from CT, MRI, and other imaging modalities. These comparatively high-resolution actual data sets have significantly increased the realism, visual fidelity, and clinical usefulness because the virtual representations are based upon real human anatomy, not upon graphic drawings or approximations.

### Table 1. Taxonomy for Several Generations of Virtual Anatomy

<table>
<thead>
<tr>
<th>Generation</th>
<th>Properties</th>
<th>Examples of applications</th>
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<tbody>
<tr>
<td>1</td>
<td>Geometric anatomy</td>
<td>3D organ shapes</td>
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<tr>
<td>2</td>
<td>Physical dynamics modeling</td>
<td>Kinematics, deformations</td>
</tr>
<tr>
<td>3</td>
<td>Physiologic characteristics</td>
<td>Bleeding, leaking bile</td>
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<tr>
<td>4</td>
<td>Microscopic anatomy</td>
<td>Neurovascular, glandular</td>
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<tr>
<td>5</td>
<td>Biochemical systems</td>
<td>Endocrine, immune, shock</td>
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One new application developed in the Biomedical Imaging Resource at Mayo Clinic could be considered the earliest example of generation 4, as illustrated in Figures 13 and 14. The purpose of generation 4 is to add microscopic-level detail to the anatomy, rendering with high fidelity such miniature size structures as neurovascular bundles and glandular structures within mucosal surfaces. Figure 13 shows a comparison of 3D visualizations of a single neuron from the inferior mesenteric ganglia of the gastrointestinal system obtained from a confocal microscope scan. The left image is a volume rendering and the right image is a surface rendering of the derived specific model. Figure 14 illustrates four virtual endoscopy views of this extraordinary model captured from a fly-through of the neuron. The upper-left panel is a close-up of the surface, and the other three panels are views from “inside” the neuron. The location of somal junctions for several dendrites can be seen, and one view (lower right) projects into a single dendritic appendage.

This fourth generation integration of histologic anatomy with gross anatomy demonstrates the potential for a seamless integration of human anatomy from gross to microscopic levels.

It is speculated that the fifth generation would be comprised of complex biochemical parameters with multiorgan system integration to represent systemic functions, such as neuro-endocrine and immunologic functions, or to show pathologic states such as shock. As successive generations are realized, the virtual representation continues to become more realistic, and hence useful. A virtual endoscopic procedure on this level of image representation might eventually become indistinguishable from the view of the actual patient and permit a continuous, seamless fly-through from a gross anatomic, to endoscopic, and finally to a microscopic visualization.

Virtual endoscopy is the fountain head of an entire generation of new diagnostic opportunities. Theoreti-
Figure 14. Four different virtual endoscopic views of the neuron model captured from a dynamic fly-through. Upper-left panel shows close approach to the model, upper-right shows view from within soma, revealing interior somal surfaces and several junctions of connecting dendrites; lower-left panel illustrates a closer view of somal/dendritic junctions; lower-right shows view looking into a single dendrite.

cally, most, if not all, internal structures can be visualized using this modality. The clinical benefits can be deductively stated, although clinical validation will be needed. No longer will the patient require a sedative, insertion of an instrument into a natural body opening or through a minimally invasive opening, or hospitalization or ambulatory center observation following the procedure, all of which increases the risk of complications and/or adds cost to the procedure. Early success will be in those organ systems of large size that have no intrinsic motion and that maintain a lumen without special assistance or preparation. Such systems include but are not limited to the tracheo-bronchial tree, renal system from calyces to bladder, pancreatico-biliary tree, uterus, cerebro-ventricular system, spinal canal, and major joints. Areas that require special attention include the upper GI tract (requires insufflation), colon (requires bowel prep), vascular tree (requires contrast material), temporal bone and inner ear (requires higher resolution), and heart (requires motion accommodation/correction). In addition to the benefits for noninvasive diagnosis, the potential exists for use of virtual endoscopy in combination with noninvasive energy-directed therapeutics, such as high-intensity focused ultrasound. And the potential has yet
to be explored in the areas of education, training, and treatment planning (Robb, 1995). Virtual endoscopy truly epitomizes a first realization of the remarkable power and promise of modern imaging and computing technologies in the Information Age.

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