Surgical Imaging Systems

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Imaging in surgery is used for diagnosis, planning, intraoperative navigation and post-operative evaluation.[1-3] Digital medical imaging modalities include computed tomography (CT), magnetic resonance imaging (MRI), MR therapy (MRT), fluoroscopy and ultrasound.[4] These modalities are applied singly or jointly (multimodality).[5,6] Surgical requirements differ according to the nature of intervention, and real-time guidance[7] is sometimes needed such that a sequence of images is generated and displayed as acquired.[8] Soft copy display on CRT screens is satisfactory for intraoperative use, while hardcopy film images or physical replica modeling may be needed in other cases. Computed tomography,[9] developed more than 20 years ago, remains important in craniofacial[10-14] and orthopedic surgery.[15] Newer imaging systems, especially ultrasound, magnetic resonance imaging,[16] and digital fluoroscopy are used for neurosurgery,[17-23] oncology, cardiothoracic24 and abdominal surgery. Each modality offers specific qualities that subserve specific needs in diagnosis, planning, intraoperative navigation[25-27] and evaluation (Table 1).

The principal modalities used for surgical applications are outlined in Table 2. No single modality serves every need in an efficient manner, and tailoring the imaging procedure and technology to match the specific requirements is a major challenge. In some instances, combinations of multiple modalities are needed to achieve the desired results. For example, an abnormal focus of activity found in a PET scan may be insufficiently defined anatomically. By combining the PET scan with a CT or MRI scan of the same body region such that the two examinations are superimposible,[6] the anatomic locus of the abnormal functional region can be identified. The process used to unite the PET and CT/MRI scans is frameless stereotaxy.[36-38]

Recent developments in imaging methods have advanced minimally invasive medicine by allowing image guidance and introduction of new therapeutic modalities, especially focused ultrasound, cryotherapy, stereotactic radiotherapy,[45] interstitial laser therapy[46,47] and brachytherapy (Fig. 1). Among these developments, the fusion of multiple images without use of a stereotactic frame[48] by frameless stereotaxy is most important. Combination of optical images derived

Table 1. Modalities and requirements served in application of imaging to surgery.

Surgical Application	Requirements	Modalities
Diagnosis	Tissue contrast	CT, MRI, ultrasound, SPECT, PET
Planning	Geometric fidelity	CT,[28] MRI
Intraoperative navigation	Geometric precision and accuracy [29,30] Real time display [31]	ultrasound,[32,33] MRT, frameless stereotaxy [34,35]
Post-operative evaluation	Lesion-tissue contrast	CT, MRI

from a video camera with previously acquired CT or MRI scans facilitates the localization of lesions and critical structures (Fig. 2).[49]

Magnetic Resonance Therapy

Intraoperative imaging in an MR scanner specially constructed for guiding and monitoring minimally invasive surgical procedures is under evaluation at several centers, especially Brigham and Women's Hospital in Boston[50] (Dr. Jolesz). This system (Fig. 3) was designed to meet the needs of interventional MR, and initial results are encouraging.[51,52]

Soft tissue structures are continuously deformable and can change significantly during the operative intervention, and so pre-operative images can only be used as a general guide to document the size,

Table 2. Modalities used in surgical imaging

Modality	Physical Basis Application	Image Types	Surgical	Limitations
CT (Computed Tomography)	X-ray absorption and scattering	• slice • volume	• preoperative planning[39,40] • postoperative evaluation	• cost • ionizing radiation
MRI (Magnetic Resonance Imaging)	• paramagnetic properties of tissues • flow	• slice • volume • cine sequence[41]	pre- and post-operative	• cost • presence of metal
MRT (Magnetic Resonance Therapy)	• paramagnetic properties of tissues • flow	• slice • volume • cine sequence	interventional therapies (navigation[42] and monitoring)	• cost • availability
Fluoroscopy	X-ray absorption / Compton scatter	image sequence at video rates	intraoperative navigation	tissue-lesion contrast
Ultrasound	acoustic scatter and attenuation	slice real-time sequence	intraoperative navigation	acoustic window required (no interposed bone or air)
Frameless Stereotaxy	multiple modalities (typically CT and/or MRI)	navigation guidance[43,44]	localization	computationally intense intraoperative changes in soft tissue geometry

position and relationship of tissues initially unless a means to update the information is available. The ability to monitor such changes is a major advantage of MRT, fluoroscopy and other real-time methods.[53]

ELECTRONIC ANATOMIC ATLAS

The conventional printed textbook anatomic atlas is familiar and important in medical education and practice. Electronic atlases have been constructed which contain the information found in the traditional printed versions, with some interesting and important new capabilities.

An electronic atlas consists of a volumetric data set from a body region with an integrated knowledge base that contains the anatomic nomenclature and ancillary information (such as tissue type, vascular territory, functional signficance, etc.) linked to the image data. By combining the stored atlas volume with interactive computer graphics rendering tools, the user can generate unique views from any desired perspective (Fig. 4).[54]

The Visible Human Project at the National Library of Medicine[55] is an important source of anatomic information. Adult male and female cadavers have been imaged by tissue section, CT and MRI at high resolution. These data are now available in the public domain and are found in many electronic atlases (Fig. 5).

3-D deformable anatomical atlas matching algorithms based on Grenander's global shape models have been developed that accommodate both global and local shape differences.[56] Anatomical shape is modeled using a deformable atlas (template) and individual shape variation is modeled using probabilistic transformations that

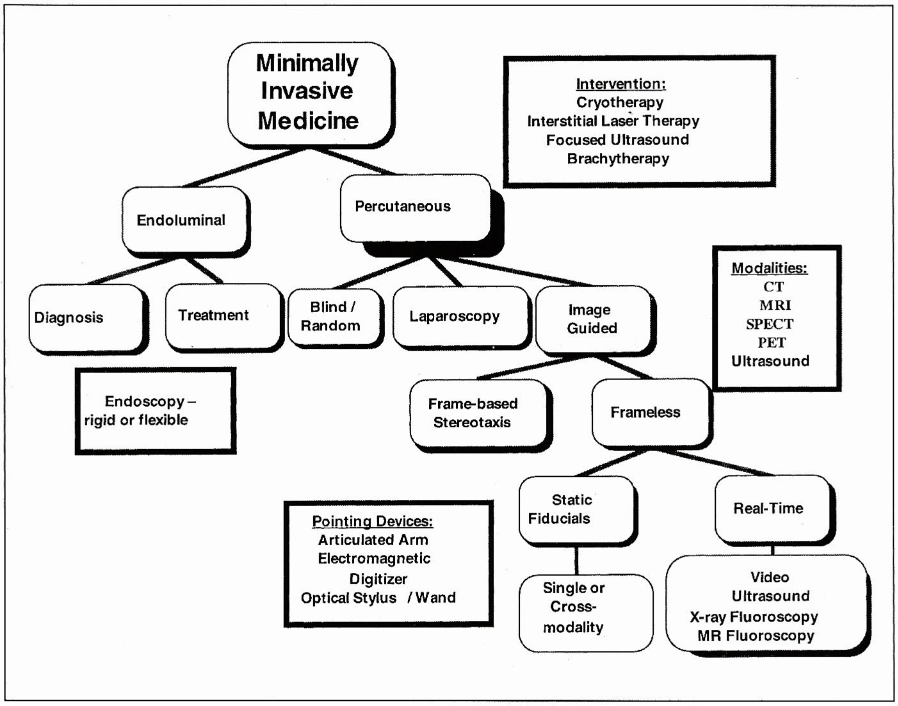

Figure 1. Minimally invasive medicine is practical as a result of new interventional therapies applied under image guidance.

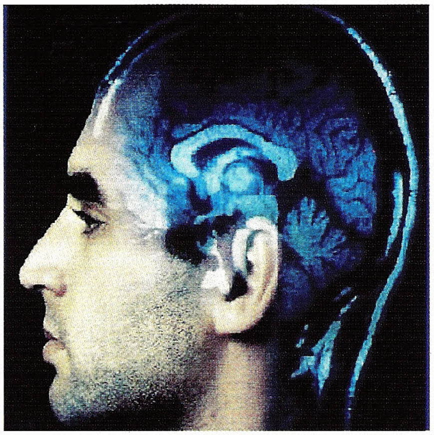

Figure 2. Integrated MRI and surface image. Combination of previously acquired volumetric images and intraoperative views of the body surface has been accomplished using methods of frameless stereotaxy. A lateral surface view of a young male subject's head has been superimposed with a midline sagittal MRI slice from a volumetric examination. (Courtesy of Kevin Shuster, Biomedical Visualization Laboratory, University of Illinois, Chicago)

Figure 3. Magnetic Resonance Therapy (MRT). A prototype open-configuration MRI system has been developed by GE Medical Systems in collaboration with Brigham and Women's Hospital (Dr. Ferenc Jolesz). This unit is now installed in the Intervention MRI Center and several additional units have been exported. (Courtesy of Surgical Planning Laboratory, Brigham and Womens Hospital, Boston, Mass. and GE Medical Systems, Inc.)

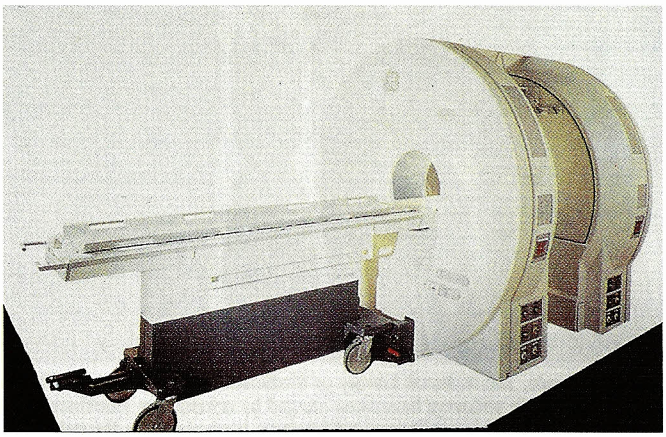

Figure 3a. Open MRI system (0.5 Tesla) with integrated anesthesia, monitoring devices and surgical tools is the cornerstone of MRT.

Figure 3b. The surgical field is placed between the paired magnets to allow direct vision of the site and simultaneous display of MR images for navigation and monitoring of therapy.

Figure 4. Electronic atlas of the head. The Voxel Man™ electronic atlas of the head contains a volumetric data set with integrated knowledge base and computer graphics software to allow synthesis of custom images from user specified orientation. The anatomic labels, tissue type, vascular territory and functional significance of structures are accessible through a graphical user interface. This software operates interactively on desktop workstations.

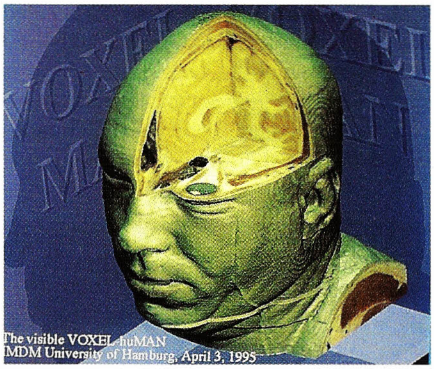

Figure 4a (above). A wedge section of the head has been removed by interactive editing of the Visible Human-male data set to reveal the internal structures from a color cryosection data set.

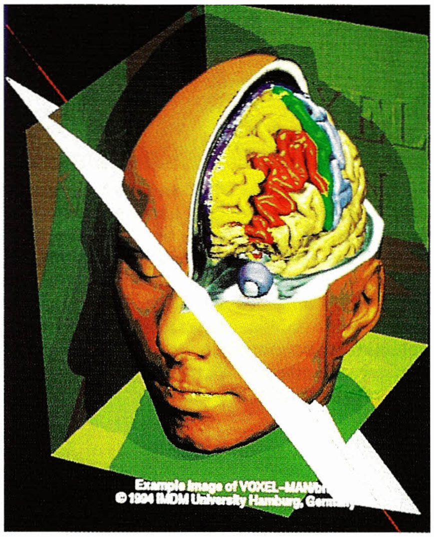

Figure 4b (above). An oblique cutting plane may be positioned interactively. The left hemisphere of the Voxel Man atlas is exposed.

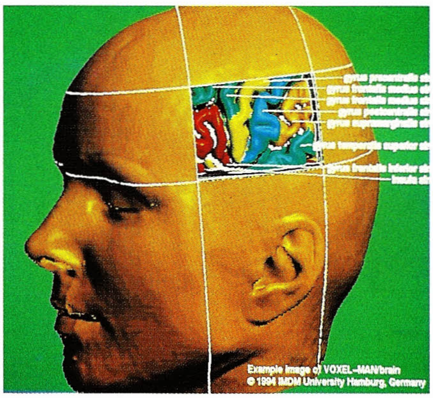

Figure 4c (above). The cortical surface of the brain is color coded and labeled in this atlas view. The colors and labels are intrinsic to the Voxel Man atlas, and may be displayed automatically as required.

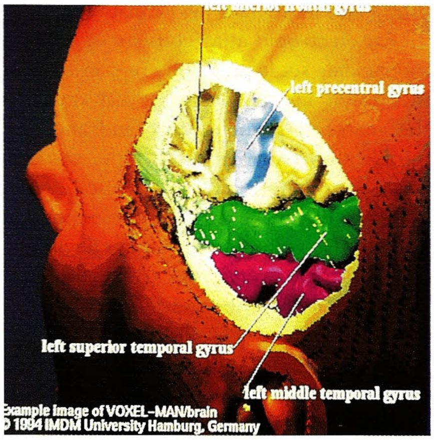

Figure 4d (above). A temporo-parietal exposure of the brain surface in this posterior oblique view of the head was generated to simulate the intraoperative exposure for neurosurgical planning.

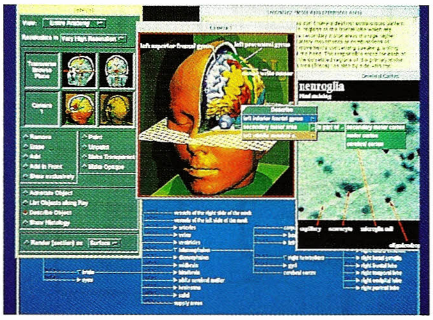

Figure 4e (above). An extensive hierarchical knowledge base is integrated with the volumetric images allowing linkage from the atlas images to on-line textbooks of neuroanatomy. (Courtesy of Prof. Karl Heinz Hoehne, IMDM-University of Hamburg, Germany.)

are applied to the atlas coordinate system. Continuum mechanical models based on elasticity and fluidity are used to constrain the transformations applied to the atlas to ensure anatomical relationships are maintained.

The deformable atlas is matched to a target volume by estimating the transformation that deforms it into the shape of a particular data set. Once deformed, the resulting individualized atlas contains information such as tissue type, structure names, landmarks and other information keyed to the target data set. Thus, the individualized atlas provides a means of automatic labeling and quantifying the shape of a particular anatomy. Analysis of the atlas transformation also provides information for quantifying shape differences and growth trajectory (Fig. 6).

A deformable textbook that mathematically represents the shape and variability of the developing cranium (skull vault) has been defined.[57,58] The textbook consists of anatomic information in the form of digitized image volumes (such as CT or MR 3-D data sets) and descriptive information such as structure names, locations, and shapes. The deformable textbook is used to generate individualized ones. Each individualized textbook provides subject specific information (like structure location, volume, shape, etc.) normally only known

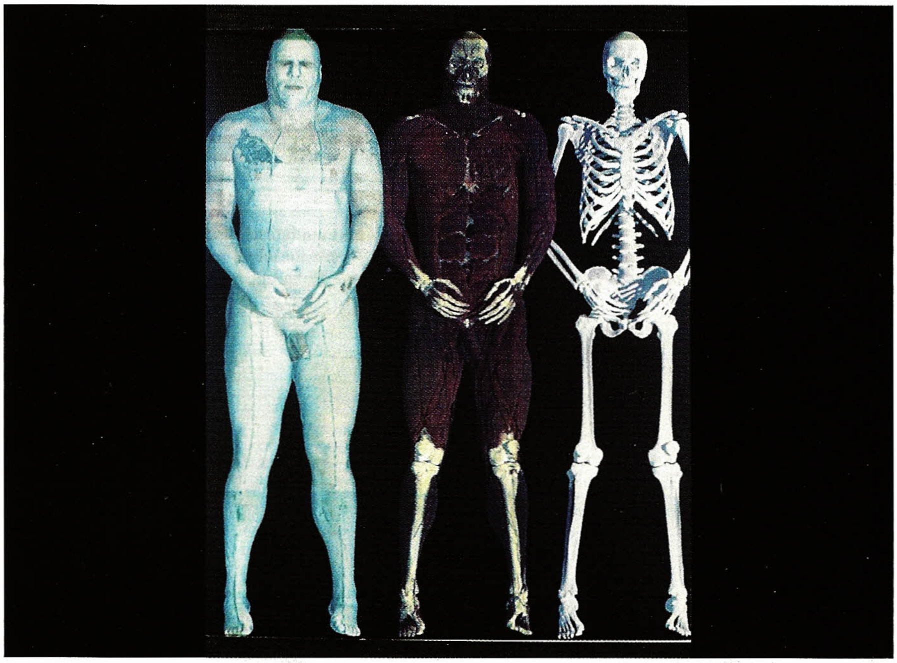

Figure 5. The Visible Human Project-male. The National Library of Medicine has sponsored the Visible Human Project where adult male and female cadavers have been imaged by cryosection blockface color scanning, MRI and CT. These data, unique in their quality and extent, have been placed in the public domain and are the basis of many anatomic reference and training systems. From the cryosection data, the skin, muscle and skeletal surface of the Visible Human-male in frontal projection have been rendered using computer graphics. (Courtesy of Engineering Animation, Inc., Ames, Iowa)

Figure 6. Synthesis of an individualized electronic atlas of the head. Global pattern matching may be applied to an electronic anatomic atlas (or "textbook") for creation of a deformed version that matches the surface and internal structure of a given subject. This process results in the synthesis of an individualized electronic atlas.

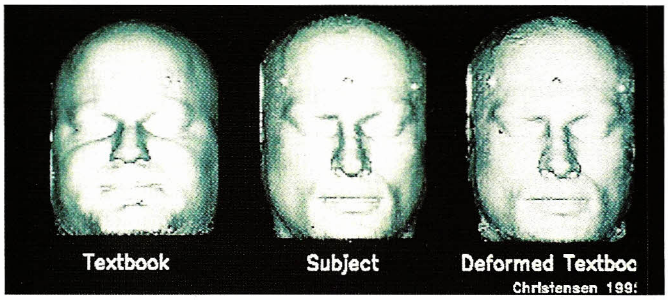

Figure 6a (above). The original electronic atlas of the head (left, designated "textbook") is matched with a specific individual (center, "subject") to create a new atlas that has the subject's shape and form (right, "deformed textbook").

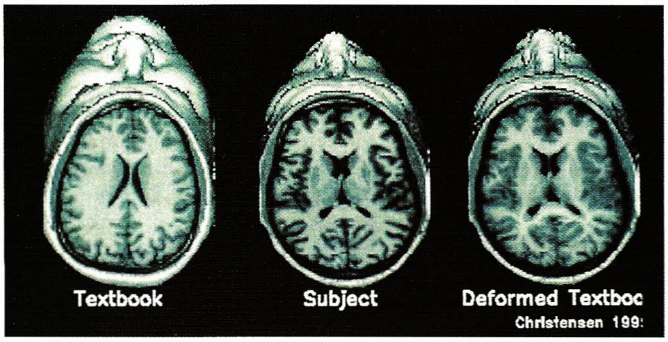

Figure 6b (above). The matching process works in three dimensions. The textbook atlas (left) and original subject (center) do not match when a slice is taken at an arbitrary level. After global pattern matching, the new individualized atlas (called a "deformed textbook", right) reproduces the size and shape of the subject and carries the label and segment information associated with the atlas (e.g., knowledge base in the Voxel Man atlas).

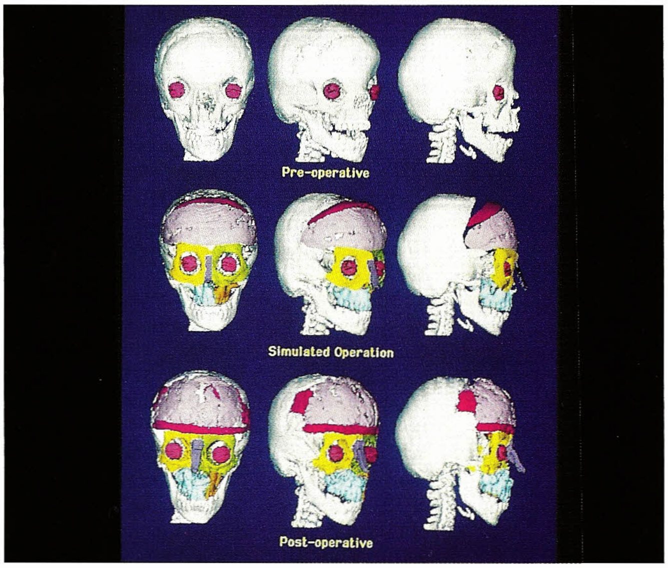

Figure 7. Craniofacial Surgical Planning and Evaluation. Interactive software on desktop workstations is used to plan and evaluate craniofacial surgical procedures. Volumetric CT data are received via an electronic network and visualization software allows display of the 3-D data. Top row shows the preoperative views of the skull in a child with hypertelorism. The ocular globes have been isolated and are displayed within the orbits. The middle row shows the result of surgical planning, performed interactively by a surgical research fellow. The bottom row was created from post-operative scans to validate the surgical planning operations and test the quality of this process. (Courtesy of Surgical Planning Laboratory, Brigham and Womens Hospital, Boston, Mass. and GE Medical Systems, Inc.)

Figure 8. Whole body optical surface scanner. Cyberware whole body optical surface scanner captures the body surface geometry by four active scanners. This device is the basis for 3-D surface anthropometry that is used to evaluate the size and shape of human populations.

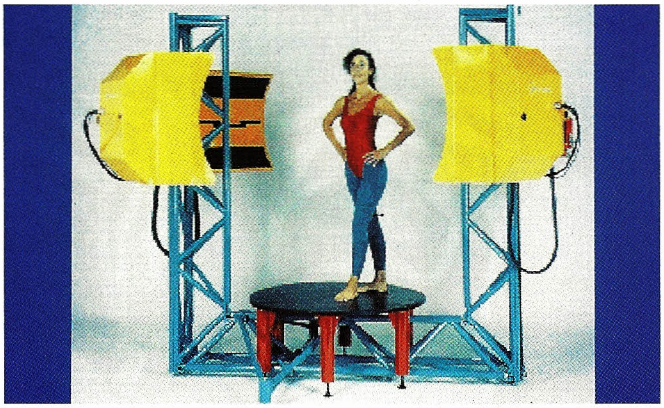

Figure 8a (above). Cyberware scanner system.

Figure 8b (above). Sample data set from an adult female seated and wearing a body suit. (Courtesy of Kathleen Robinette, CARD-Armstrong Laboratory, Wright-Patterson AFB, Ohio and Cyberware, Inc.)

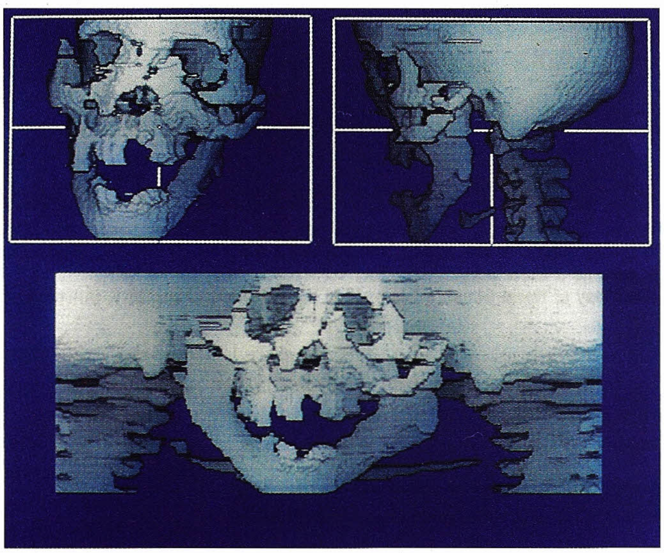

Figure 9. Unraveling the facial skeleton into a planar map. Multiple comminuted facial fractures in a young male were imaged by computed tomography and displayed after 3-D reconstruction. Frontal (top left), left lateral (top right) and panoramic views of the facial skeleton are displayed. By unraveling the scan volume into a planar map, the orientation and relationship of fracture fragments is conspicuous. (Courtesy of Kevin Shuster, Biomedical Visualization Laboratory, University of Illinois, Chicago)

Figure 10. Unraveling the colon for virtual endoscopy. Tracking the colon in volumetric spiral CT scans is the basis of virtual endoscopy.

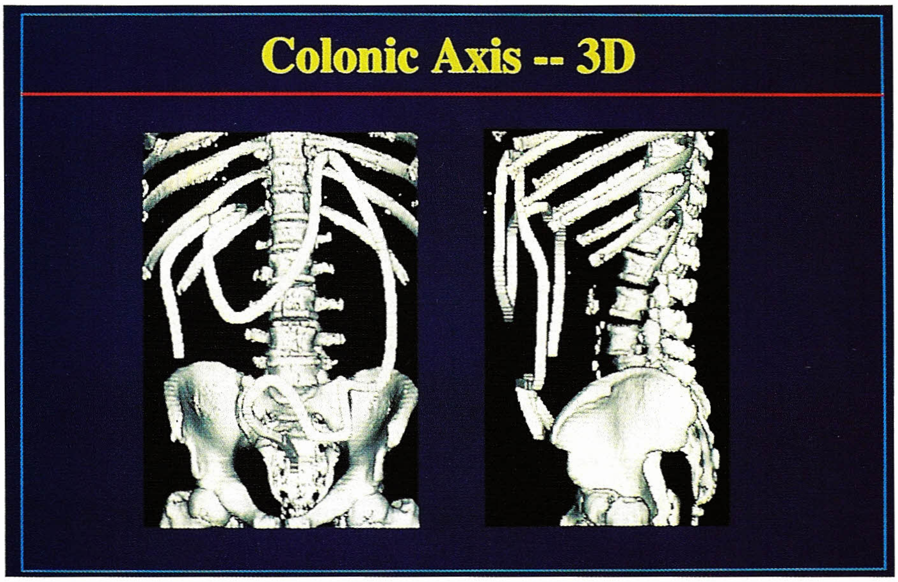

Figure 10a. The path of the colon has been identified and fit with a spline curve. The abdominal spiral CT scan was performed in a single 30 second acquisition on a Siemens Somatom Plus S scanner.

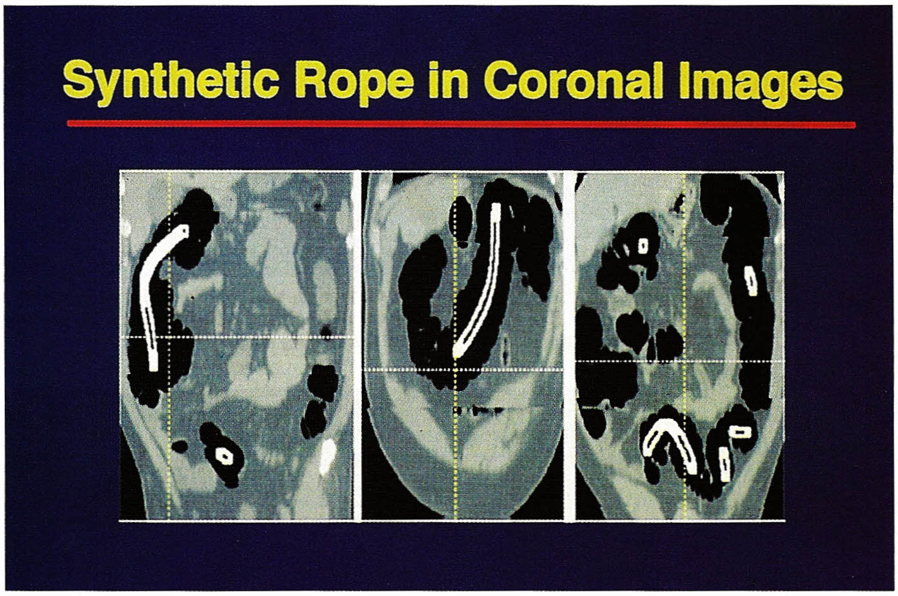

Figure 10b. Coronal, transverse and sagittal multiplanar slices are generated in real time with a crosshair cursor at the same point within the color on all 3 views. The synthetic "rope" within the colon is seen as a white tubular structure located centrally in the lumen.
(Courtesy of Kevin Shuster, Biomedical Visualization Laboratory, University of Illinois, Chicago)

for the textbook anatomy. It is generated by deforming a generalized textbook into the shape of a particular individual's anatomy (Fig. 6).

SURGICAL SIMULATION

Computer-based imaging for simulation surgery implies graphical display and manipulation of anatomy, typically derived from volumetric CT and MR imaging.[59,60] Virtually any surgical procedure can be simulated, although this does not imply that the simulation will be accurate, complete, useful, nor that it can be accomplished efficiently. In fact, it may be the case that simulation of a surgical procedure is more complex, awkward and difficult to perform than the procedure itself.[61] This is especially the case when a surgeon is involved that has relatively little computing experience. Improvements in interactive computer graphics and the availability of networked low cost desktop graphical workstations allows the pre-operative visualization of complex anatomic abnormalities,[62] surgical planning[63-65] and post-operative evaluation (Fig. 7).[66]

RECENT IMAGING DEVELOPMENTS

Optical surface imaging of the whole body for 3-D anthropometry is underway at Wright-Patterson Air Force Base and several other sites.[67] This instrument captures the external body surface by non-contact scanning and is used for summarizing the size and shape characteristics of human populations (Fig. 8).[68] The optical scanning technology used for anthropometry has been integrated with volumetric medical images from CT and MRI to create a superimposed visualization for intra-operative use (Fig. 2).[69]

Cartographic mapping techniques are employed to synthesize panoramic views of the skull (Fig. 9).[70] These images simplify the interpretation of volumetric CT and MRI scans, especially for comminuted fractures of the facial bones.

Virtual endoscopy is a collection of methods applied to imaging the bowel noninvasively. After a volumetric CT or MRI scan, the colon is identified and visualized using techniques that simulate endoscopic methods (Fig. 10).[71]

Many technologies are adaptable to surgical imaging requirements, and depending on the ingenuity of investigators , engineers, physicists and computer scientists, we can expect to see further innovations and continued growth of these applications in the future. **STI**

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