Chapter 12

3D MEDICAL INFORMATICS

Information Science in Multiple Dimensions

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Chapter Overview

This chapter describes the emerging discipline of 3D Medical Informatics. While text-based informatics has a distinguished history and accepted fundamental linguistic principles, the use of 2D and 3D data in informatics has emerged relatively recently as computing capabilities have rapidly advanced, imaging and modeling standards have been established, and as high performance networking has made possible the sharing of the large and complex data that images, volumes, and models represent. This chapter outlines the early developments of this discipline, presents some examples of how image data is managed and presented, and suggests some of the leading research challenges in this young field.

Keywords

content-based retrieval; visualization; volume rendering; digital image archiving

1. INTRODUCTION

What is 3D informatics? Simply, this term applies to the study of informatics or information sciences associated with images, volume data, and other dimensional data in addition to the text-based metadata that surrounds such information. Libraries and other archival institutions are fast becoming repositories for complex information, non-print materials including audio recordings, film and video collections, and sophisticated scientific data. Tools to index these collections are rudimentary today, relying solely on textual descriptions of their contents and routine indexing of the annotated bibliographic information. Today's advanced computing and networking environments enable the distribution and display of high dimensional data beyond simple text. 3D informatics is the study of how to manipulate and manage these complex data.

> 3D Informatics: the science concerned with the gathering, manipulation, classification, storage, retrieval, representation, navigation, and display of complex, high-dimensional data. This data may include more than three independent dimensions, including position, time, and scale. The data may also represent many more than one dependent dimensions, including multichannel data (e.g., the RGB values of the Visible Human Project color cryosection data).

There are strong analogs between text-based informatics and the concepts of visual and 3D informatics. For example, in 1992, the U.S. National Science Foundation held a workshop to "identify major research areas that should be addressed by researchers for visual information management systems that would be useful in scientific, industrial, medical, environmental, educational, entertainment, and other applications." Participants helped to shape research positions in the many disciplines involved in framing the overall field (Smeulders, 2000). These disciplines include shape segmentation, object recognition, feature extraction, indexing, similarity metric development, display and feedback. These elements, while very different in their implementations and founding scientific principles, fill similar roles as their counterparts in text information management systems. Figure 12-1 shows the basic algorithmic components for information retrieval from text-based data collections. Compare and contrast this view of data flow in text-based informatics with a similar structure in Figure 12-2 showing the data flow of query by pictorial example in a visual information management system.

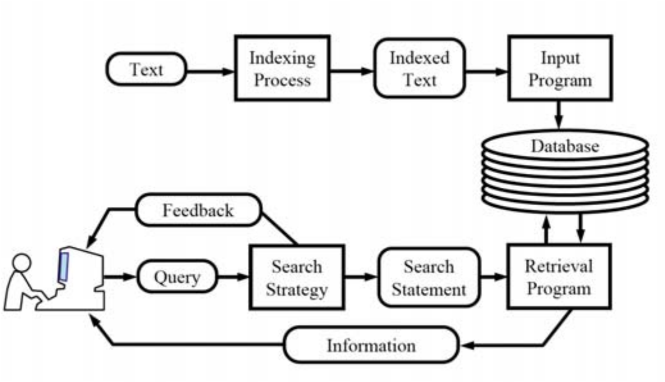

Figure 12-1. A simplified informatics view of the data flow in text information retrieval.

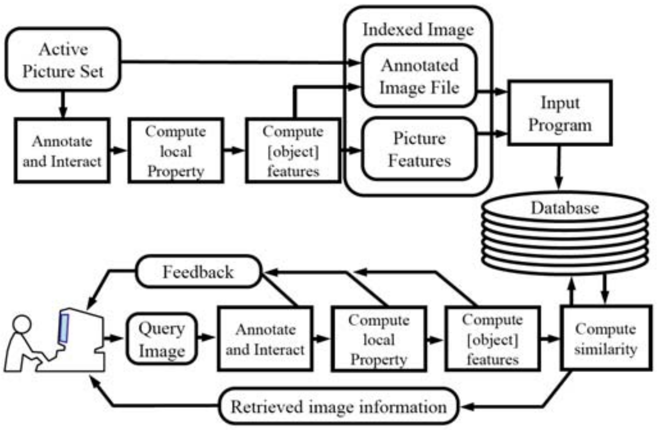

Figure 12-2. Basic algorithmic components of query by pictorial example. This data-flow diagram has many features in common with the data retrieval methodology described in Figure 12-1. (Adapted from (Smeulders, 2000)).

In the area of high-dimensional data management systems, developing and understanding the processes of deriving syntactic and semantic knowledge from the complex data are active areas of research. Where images are involved, deriving local visual properties, detecting shapes and deriving their features, and exploiting those features as indexing tools are problems at the forefront of 3D informatics research (Castelli, 2002). Shape features derived from objects identified in the images or data often require complex analyses arising from the topology or geometry of the object under study. Hilaga, et al., describe the use of topological abstractions known as

Reeb graphs to index collections of 3D graphical models. Given a representative shape, their methods permit the retrieval of comparable shapes from the collection (Hilaga, 2001). Funkhouser, et al., have been using mathematical methods such as spherical harmonics and automatic symmetry detection on 3D graphical models to index large collections aggregated from the World Wide Web (Funkhouser, 2003). Their sketch-based retrieval system permits query-by-sketch, attempting to match primitive 2D sketches of objects to collections of complex 3D models; it has been online since 2001.

The areas of informatics that are based on textual data are far ahead of their visual analogs. Linguistics and computer science in the form of artificial intelligence and natural language processing are driven to understand text, investigating techniques in lexical analysis, parsing, and semantic discovery. Two-dimensional or volume image informatics have not had similar intensive explorations. What has been achieved are a series of early models for extracting features from images using transfer functions and low-level image processing, partitioning datasets into cohesive, contiguous regions using segmentation, studying the shape properties and generating digital models of objects, and presenting these objects to expert users for study and knowledge integration. Developing these early separate methods into knowledge discovery systems is the current challenge.

Despite the emphasis on image processing, shape recognition, and automated indexing, 3D informatics is not a simple outgrowth of fields of computer graphics or image processing. 3D informatics incorporates additional research areas including content-based retrieval, image understanding, indexing, data mining, and data management. When such methods of high dimensional data analysis are applied to problems involving 2D images and 3D volume data in medicine, the result is 3D medical informatics.

The remaining sections of this chapter concentrate on this specific area. The next section begins with an overview of 3D medical informatics, including the roots of the discipline as well as some examples of motivating applications for why it is an important area of exploration. Two subsequent sections are in-depth descriptions of examples of 3D medical informatics. The last two sections are a statement of some of the grand challenges in this research area as well as a summary and conclusions for this chapter.

2. OVERVIEW – 3D MEDICAL INFORMATICS

Consider a possible scenario in 3D medical informatics. Some time in the not-too-distant future, a pathologist looks through his stereo microscope at a tissue sample, taken in a biopsy of a patient. There is something distinctive about the architecture of the tissue that he is viewing, but what he is seeing is beyond his experience. He calls a colleague and she places the sample in a 3D confocal microscope to acquire a digital volume image of the sample. Together, they perform some simple computer operations on the resulting data to derive some fundamental image metrics, and then use the sample 3D image and the derived metrics to search a distributed public data repository for comparable data. The request can be paraphrased as, “I’m sending you a picture. Send back pictures like this one along with clinical information, diagnosis, treatment, and prognosis of similar patients.”

Within minutes, five comparable cases have been found. The pathologist reviews the images and decides that only four of the five are relevant, and the pathologist proceeds to download and read the case histories of the comparable patients. In three of the remaining cases, a diagnosis of “Disease A” was made, and the condition was resolved through medical treatment with the patients making full recoveries. The fourth case could not be controlled with medical treatment, so additional CT scans were taken, 3D reconstructions of the affected tissue were made and interventions planned with computer assistance, and subsequently, surgery and other therapies were attempted. Ultimately, the diagnosis was modified to a completely different disease, “Disease B,” the treatment switched, and the patient made a full recovery. The pathologist reviews the five cases and their histories complete with accompanying volumetric image data.

Armed with this information, the pathologist recommends to his patient and the original referring physician that the prognosis is likely to be good, that a most likely diagnosis would be “Disease A,” but the primary care physician should take special care to order additional tests to rule out a diagnosis of “Disease B.”

This hypothetical example is a scenario that utilizes query by pictorial example to solve a medical problem. Both automated and visual comparisons are used to ascertain the relevance of the retrieved cases. An initial prognosis is given based on the number of comparable cases returned and the general consensus among the related cases that the condition is treatable and all five had full recoveries. Secondary findings are also indicated, and the referring physician is warned to rule out other causes. Also assumed in this discussion are facilities to acquire high dimensional data at multiple resolutions, the existence of methods to display and manipulate multidimensional data to develop surgical plans, and multiple means of indexing and retrieving complex image and text data using both images and text as sources of query information. While not routine today, the time is not far off where such capabilities and facilities are commonplace; the algorithms, methods, and technologies are currently being developed.

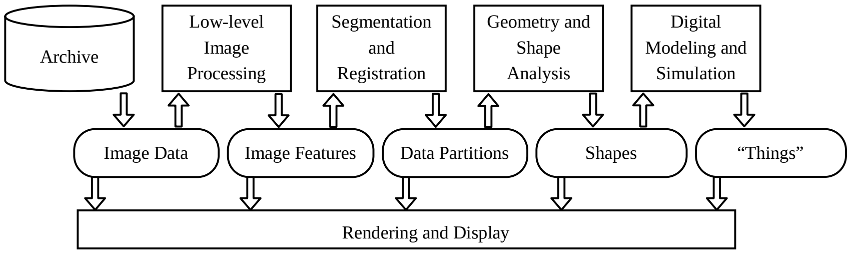

Figure 12-3. An idealized view of the medical visualization pipeline. This part of 3D Informatics encompasses the study the process of medical visualization by research in the four core areas of Volume Image Archives, Low-level Image Processing, Geometry and Shape Analysis, and Digital Modeling and Simulation. Note that the results of many of the subfields can be directly rendered, revealing the information that is hidden within the dataset at different levels of abstraction. One attribute of any informatics program is the progressive abstraction of volume information from image to model.

2.1 From Data to Knowledge

The greater part of this chapter will consider the enterprise of medical visualization from data storage and retrieval to the rendering of the final visual presentation; conceived as a pipeline, the process is seen to be connected and yet divisible into separate subfields that can be studied and improved (See Figure 12-3). Every process in a 3D medical informatics pipeline has the potential for interactive feedback and display. This treatment will not ignore the problems of data retrieval, but rather concentrate more heavily on those elements not shared with text informatics.

Informatics is often a building of abstractions from which knowledge can be synthesized. For instance, a taxonomy of life forms builds from the characteristics of individuals sharing traits, to species, to genus, eventually to the basic abstraction of kingdoms such as plant or animal.

A similar progression is seen in 3D medical informatics. Consider the simplified pipeline in Figure 12-3. As information is passed from left to right, it is refined and higher-level abstractions are created to describe the concepts contained in the volume data files. The progressive refinement of volume data and other multi-dimensional information from raw image, to embedded shapes, to recognized objects, to anatomical models is the focus of this treatment of 3D medical informatics.

2.2 History

3D medical informatics is a very young discipline. As with all information science, technology is the key driving force that accelerates its development. However, while the study of semantic knowledge in linguistics and text-based information had been studied for decades prior to the development of computer technology, 3D medical informatics was essentially created with the advent of the computer.

At the turn of the 20th century, Roentgen discovered x-rays and applied them to imaging the human body, creating a revolution in both physics and medicine, earning him the Nobel prize. This revolution did not extend to a comparable development in imaging informatics. While publishers of textual information had centuries of developed experience in printing, publishing, and distribution, imaging sciences had no comparable experience in these endeavors. Moreover, the media for storing the resulting medical images and data were fragile, flammable, difficult to copy, and impossible to distribute widely. Thus, while there was intense development in using medical images, there was little advance in indexing, cataloging, and understanding the information captured in early radiographs.

CAT scans, or more precisely X-ray computed tomography only arrived much later in the century. The mathematical principles for tomographic reconstruction were first published by Johann Radon in 1917. More than fifty years transpired before the technology and engineering of x-ray detectors and computers matured sufficiently to enable the creation of medical scanners. For this engineering feat, Allan Cormack and Geoffrey Hounsfield were independently awarded the Nobel Prize in 1979. The resulting systems are routine tools in medicine today and constitute a multi-billion dollar industry. Practical Magnetic Resonance Imaging (MRI) awaited affordable superconducting magnets, but now is an essential tool in many hospitals and radiology practices. The development of practical high-resolution 3-dimensional scanning set the cornerstone for modern imaging in medicine.

Simultaneously, emerging computer and network technologies facilitated the storage, reproduction and distribution of complex medical image data. An industry of Picture Archiving and Communications Systems (PACS) technologies rapidly established itself, requiring that more and more sophisticated data indexing and retrieval methods be applied to medical image collections. The creation of standards for DIgital COmmunications in Medicine (DICOM) have helped to make these areas more interoperable. Computers and their associated technologies have enabled all of these developments. Although the revolution in imaging sciences was started by

Roentgen, imaging informatics was finally enabled by the advent of widespread, interconnected, digital computing.

In 1986, the National Science Foundation (NSF) held a workshop on Visualization in Scientific Computing (McCormick, 1987). In their report, the panelists outlined a programmatic need for new developments in image understanding, networking, standards, visualization algorithm design, computer graphics hardware, and other related technologies. In the years following the NSF report on visualization, commercial and university interests have applied themselves to many of the tasks foreshadowed by the panelists. Since that time, the academic and industrial research communities have achieved some dramatic successes.

For example, while the domain of illuminating 3D data in medicine remains a conceptually difficult problem, the technical aspects for rendering multidimensional scalar data have been largely overcome. The human visual system is not accustomed to seeing both the surfaces of things as well as their interiors, so new metaphors for transparent and textured surfaces were needed and the methods and algorithms to generate them from volume data. In 1987, Lorensen and Kline published the Marching Cubes algorithm, setting the standard for extraction of surfaces from volume data (Lorensen, 1987). Shortly afterward in 1988, Drebin, et al., and Levoy independently developed raycasting methods for directly rendering shaded views of volume data (Levoy and Drebin, 1988). Alternate approaches to raycasting volume rendering were soon proposed (Westover, 1989) and accelerated parallel methods also introduced (Yoo, 1992). Volume rendering techniques were merged with computer graphics texturing hardware in 1994, enabling truly

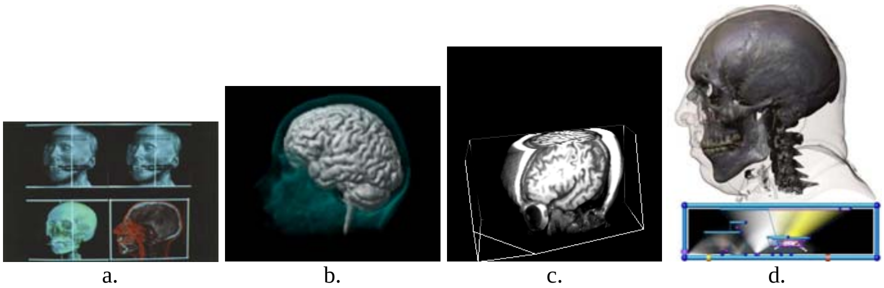

Figure 12-4. Volume rendering: A chronological progression of interactive volume rendering techniques: (a) Splatting [Westover, 1989]; (b) parallel raycasting with interactive segmentation [Yoo, 1992]; (c) texture-based volume rendering (Circa, 1997) [Cabral, 1994]; (d) interactive multidimensional transfer functions on PC hardware [Kniss, 2001]. The progression shows a trend from software to hardware, from special to general purpose, and from interactive speeds of 0.25 to 20 frames per second.

interactive visualization of volume data (Cabral, 1994). Navigation and exploration of volume data is now possible at rates of 20 frames per second on PC hardware with dynamic user control over viewpoint, transparency, and illumination (Kniss, 2001). This progression shows a successful transition over more than a decade from the development of new methods, through their engineering refinement, to product development, and finally the release of these methods as commodity tools for a broad medical audience.

Algorithmic developments are not the only successes for 3D medical informatics. Pilot studies in data collection, distribution, indexing, and content-based retrieval have advanced significantly in the last decade, and are partnered with the emergence of accepted public sources of information, common conventions, and shared tools. The Visible Human Project™ provided one of the most advanced studies in human gross anatomy to be shared widely among the 3D medical informatics research community. The availability of common data helped to accelerate the growth of visualization systems in medical settings (Ackerman, 1998). However, two datasets are not sufficient to study the nature of collections, and work on large volume medical data collections has grown in recent years (*e.g.*, Tagare, 1997, Leiman, 2003).

In the areas of segmentation, object recognition, and image understanding, new efforts in consolidation and interoperability are helping to unify research in disparate areas. Public tools for analyzing complex imaging data have recently emerged to assist in developing common conventions for processing, indexing, and understanding volumes. For example, the National Library of Medicine has sponsored the Insight Toolkit (ITK) as a common API for the segmentation and registration of 3D and higher dimensional data (Yoo, 2004). Common tools and conventions for image understanding are as essential in 3D medical informatics as shared ontologies are to conventional text-based informatics as well as cataloging systems are to the library sciences.

2.3 Why study 3D Medical Informatics?

3D Medical Informatics has compelling and innately satisfying motivations. From its early introductions, the value of X-ray CT scanning as immediately and intuitively recognized, and hospitals worldwide began investing in CT scanners. Medical visualization and 3D informatics similarly generate an immediate resonance with surgeons, developmental biologists, and other disciplines requiring navigation of the human condition where knowledge of spatial relationships is required.

Anatomy instruction is one area where 3D medical informatics has strong justification and sound foundations. The Visible Human Project™ data fostered a range of publications and educational products targeting all instructional levels from secondary school to graduate medical education. Beyond books and dissection software, there have been significant attempts to integrate 3D interactive file formats with multiple imaging modalities and existing anatomy ontologies. K.H. Höhne and the Voxel-Man software development team at the University of Hamburg have been using advanced rendering techniques to display and navigate complex information and have released digital products through a commercial publisher at a cost comparable to traditional textbooks (Höhne, 2000). Multimedia products such as these may represent the future of anatomy instruction.

Beyond instruction, 3D medical informatics has direct applications in surgical planning and intervention, transforming information into knowledge, providing clarity for critical decisions. Advanced instrumentation and rapid 3D analysis of surgical situations are becoming routine, integrating acquisition technology with interactive analysis and dynamic feedback during surgery (Jolesz, 1997). Operating rooms with integrated scanning devices and computer displays are now commonplace.

This effort is not limited to just three dimensions, and researchers routinely invoke time varying data and multimodal, multiscale radiological information in their investigations. Many diseases involve chronic, degenerative conditions that must be tracked over time. It is the progression of the condition as much as the immediate situation that is of concern to patient and physician alike. Critical areas of 3D medical informatics research include the recall of previous relevant examinations, the fusion of previous studies of the same patient with current cases, comparing the progress or the contraction of the disease. One example of the tracking of time-varying chronic diseases, is the study of multiple sclerosis, a condition involving repeated scarring of the insulating layers of nerve cells. These inflammatory attacks flare up and subside over time, and tracking the condition using spatial references to show where new lesions are appearing as opposed to older scar tissue using modern imaging allows clinicians to study the physical aspects of the disease as well as the neurological effects. These studies require the comparison of multiple images of the same patient, taken over the course of years, and align and compare the results (Kikinis, 1999). Such studies are giving new hope to patients and clinical scientists that some means may be found for controlling the disease.

In addition, the processes of 3D medical informatics can be applied in other domains. A study of topological image metrics based on juxtaposition and arrangement was published as a means of indexing medical image collections (Tagare, 1995). These metrics are invariant with respect to size and color, making them suitable for comparing images of arbitrary resolution, for instance, permitting the comparison of pediatric with adult cases. The study of such size and illumination invariant metrics has been now successfully applied to tracking marine mammal migrations where cetaceans are tracked by photographs taken of their fins. Identifying an animal from a photo of its dorsal fin by comparing the image with a veritable mug-shot catalog of dorsal fins is tedious and error-prone work. Adapting the work of Tagare, et al., this process has been streamlined from hours of visual canvassing to seconds of automated searching. Size and illumination invariant content-based retrieval techniques are changing the way marine biologists conduct their research (Hillman, 1998).

3. EXAMPLE: 3D MODELS AND MEASUREMENT OF NEUROANATOMY ACROSS SUBJECTS

Recall from Figure 12-3 that 3D medical informatics can be considered as a progression of processes applied to datasets. What are these stages? What are the input data and output data for each of these processes?

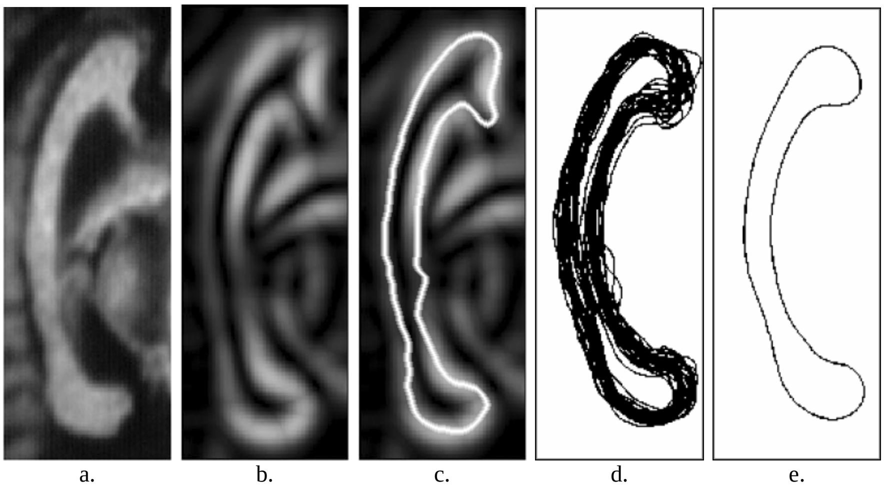

Figure 12-5. A progressive view of modeling the corpus callosum across multiple subjects. 5a: mid-saggital MR image of a human brain cropped to show the corpus callosum; 5b: *Low-level image processing* – cropped image from (5a) after a simple gradient magnitude edge detector has been applied; 5c: *Segmentation*: shape segmented using the edge strength image in (5b); 5d: *Registration*: outlines of the same structure registered across 30 subjects showing the normal (expected) variation in shape within a sample population; 5e: the average or mean shape of a corpus callosum. (Adapted with permission from Szekely, et al. (Szeke1y, 1996)).

The answers depend on the particular application and the methods being applied. In this section, we will explore these questions through the processes of modeling and measurement of deep brain structures across multiple subjects.

This example is largely described in terms of 2D models and has been drawn with permission from the work of Szekely, et al. (Szekely, 1996). Derivative work has been applied to full 3D models and has been used to study structural trends in schizophrenic patients across multiple subjects (Shenton, 2002). While this work concentrates on relatively familiar frequency-based Fourier shape descriptors, later related work has explored deformations of medial shape descriptions as well as statistical moments of point distribution models.

3.1 Indexing Images with 3D Medical Informatics

Following the progression in Figure 12-5, consider the corpus callosum, the dense white matter of connecting nerve fibers in the center of the brain that bridges the two hemispheres. If only the middle plane of the brain is considered, the vertical saggital plane that denotes the bilateral symmetry of the human body, the resulting image of the corpus callosum is an elongated arcing shape (see Figure 12-5a). Architectural defects in this structure are often linked to mental health disorders, and tumors in this region are difficult to treat unless detected early. Finding this structure in a brain scan and comparing it with “healthy” examples requires first detecting the edges in the image (low-level image processing) (see Figure 12-5b), then partitioning of the image into shapes and the matching or registration of shapes across multiple samples (segmentation and registration) (see Figure 12-5c,d). Once a shape is found, an analysis of the shape extracts features of the object (geometry and shape analysis). Based on this analysis of object features (usually across multiple samples), an object similarity metric can be created and dynamic models or templates of the structure can be formed for object detection and comparison (digital modeling and simulation).

Once segmented and aligned, the 30 cases in the training set are further analyzed for the normal or expected variation between these healthy subjects. A decomposition of the 2D shapes is performed, ordering the primary forms (eigenmodes) of deformation needed to match one shape to another. An average shape can be extracted from the set, and similarity or differences among the shapes can be derived (see Figure 12-6).

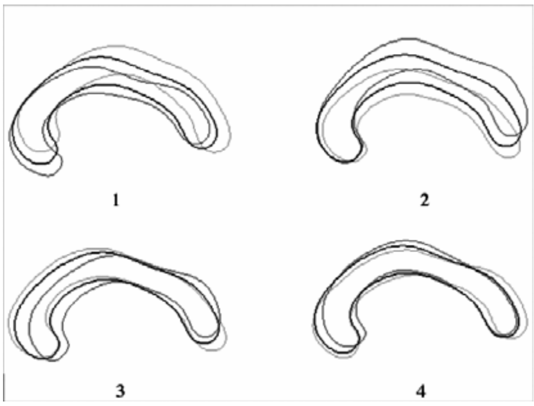

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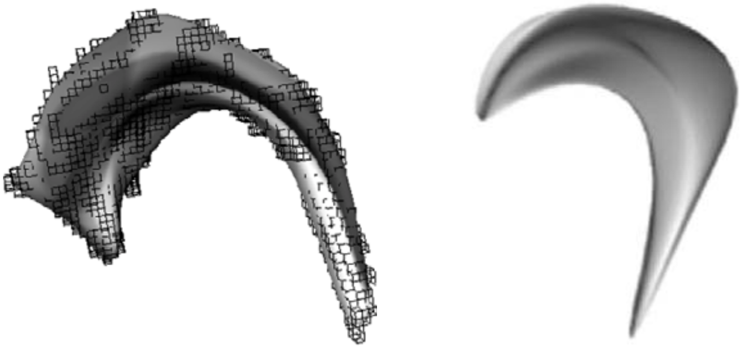
Figure 12-6. The first four eigenmodes of the deformations of the 30 objects in the training set. The calculations are based on contours represented by Fourier descriptors, which are normalized only with respect to the choice of the starting point. The deformation range amounts to eigenvalues. (Adapted with permission from Szekely, et al. (Szeke1y, 1996)).

The resulting metrics can be used to improve the automated segmentation of new subject data, and they can also be used as indexing tools for collections of MR scans of human brain structures.

3.2 Generalizing Elastic Deformable Models to 3D

This work has been generalized to 3 dimensions, permitting the analysis of solid shapes rather than simple 2D figures. Figure 12-7 shows the same strategy applied using active surfaces (as opposed to active contours) and spherical harmonics (as opposed to circular harmonics) to the caudate nucleus, another deep brain organ. The resulting digital models and the deformation metrics provide shape indices that can be used to provide quantitative comparisons of human anatomy and to catalog collections of volume data of human subjects.

An in-depth description of the work of Szekely, Kelemen, Brechbüler and Gerig is beyond the scope of the lay introduction intended here in this chapter. Their process includes a sophisticated automatic segmentation technique that uses both a frequency-based Fourier decomposition as well as an energy-minimizing elastically-deformable active-contour approach for reliably finding the corpus callosum. For a full description, see their comprehensive paper (Szekely, 1996) or their later work (Kelemen, 1999).



a. b.

Figure 12-7. An example of this technique in 3D dimensions showing a parameterized description by spherical harmonics of the caudate nucleus, a deep brain organ. 7a: model of up to degree 8 showing the original voxel object overlaid as a wire-frame structure of the voxel edges; 7b: a segmented caudate nucleus using the elastically deformed model from (7a) using spherical harmonics up to degree 5 (108 parameters). (Adapted with permission from Szekely, et al. (Szeke1y, 1996)).

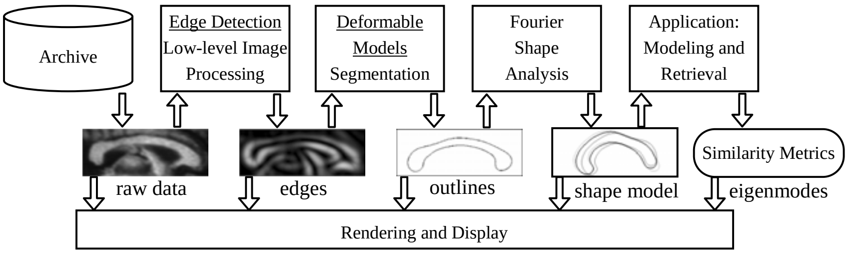


Figure 12-8. A 3D medical informatics pipeline using elastic deformable models of the corpus callosum as a case study. The data transforms left to right from raw image information to image features (edges), to segmented shapes (outlines), to controlled shapes, to similarity measures that can be used to improve segmentation, to capture normal (expected) human variation, or to index image collections.

Using this example as a case study, we can revisit the view in Figure 12-3 and map some of these methods to the stages of the processing pipeline. The resulting view is show in Figure 12-8. These or related processes are required elements of any 3D informatics application.

4. SURGICAL TEMPLATES: A CASE STUDY IN 3D INFORMATICS

3D medical informatics can have a direct influence on intervention and treating humans. Some of the most interesting rendering technologies today are appearing as 3D printing devices capable of directly creating tangible objects as “rapid prototypes” of instruments or devices. In this example, a team at the NLM’s Office of High Performance Computing and Communications has combined surgical planning techniques with computer aided manufacturing systems to create custom surgical aids for orthopedic surgery. Our application area is planning and controlling the trajectories of pedicle screws for spine surgery. The goal is to manufacture a physical jig that conforms to the contours of the patient’s vertebrae. The jig is constructed with holes that correspond to the trajectories of the pedicle screws. These holes guide the drill placement and depth, increasing the accuracy and precision of screw placement (Figure 12-9). These devices are created for each individual patient, one per segment, and improve accuracy without the introduction of navigation tools or increased fluoroscopic radiation dose. The intent is to use a jig to transfer the surgical plan directly to the operating room without introducing additional technology. The complexities of computer-assisted surgery remain in the laboratory without intruding into the operating room.

This section addresses the design issues for the surgical planning and template design workstation. Our prototype is an interactive modified texture-based volume rendering program (Cabral, 1994) augmented with physical user interface devices, 3D stereo viewing, polygonal primitives, and tools for constructive solid geometry (CSG) to serve as the computer aided design foundation for modeling templates.

4.1 Background and Related work

Figure 12-9a shows the basic problem faced in spine procedures. Appliances such as plates and rods require fixation through narrow channels called pedicles. Trajectories through these narrow isthmuses of bone have optimal placement and limited tolerances. Complications can arise when the screws accidentally enter epidural or spinal spaces and transect the spinal cord, constrict the emerging nerve roots arising from the ganglion, drift through a disc, or emerge through the anterior surface and cut the aorta.

Figure 12-9b shows the goal of our project, the creation of custom drill guides designed to mate closely with individual vertebrae that limit depth and provide for precise control of the screw path. Other groups have also pursued templates for pedicle screw placement. Radermacher and Birnbaum have reported favorable results using numerically controlled (NC) machine tools to create plastic templates (Birnbaum, 2001).

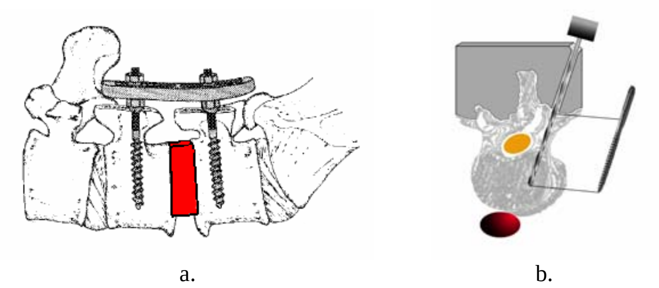
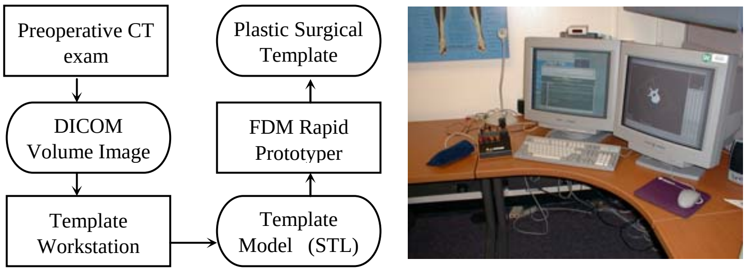


Figure 12-9. Patient Specific Surgical Instrumentation (PSSI) for the precise placement of pedicle screws required for many spine procedures. Figure 9a: lumbar plate secured with pedicle screws. Figure 9b: Our goal – a proposed template, guiding the drill path and depth. Structures such as the spinal cord, nerve roots, and the aorta must be avoided.

Our approach differs from theirs in our use of Fused Deposition Modeling (FDM), an alternate technology for creating the templates. Many affordable NC machines are limited to three axes of control. This prevents many NC machines from supporting the complex geometries required to create custom templates. By contrast, FDM is the successor to stereolithography in rapid prototyping technology. It is flexible and accurate, capable of creating a wide variety of geometries, well beyond those needed in pedicle screw placement procedures. Stratasys, a manufacturer of these rapid prototyping devices, has secured U.S. FDA approval for the generation of 3D models for diagnostic purposes. The requirements of high fidelity reproduction necessary for diagnosis are equally important in intervention. They also supply a production material that can be sterilized for use in medical procedures.

4.2 Design and Software Tools for Template Planning Workstation

We built our surgical planning workstation around an interactive volume rendering system. Recent trends in graphics workstations have led to the emergence of 3D transparent textures, enabling interactive volume rendering using conventional graphics primitives (Cabral, 1994). Figure 12-10 shows the process and the console.



a. b.

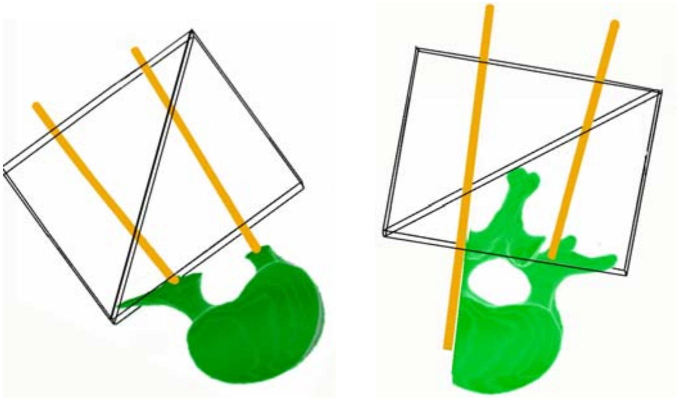
Figure 12-10. Patient Specific Surgical Instrumentation procedure and console. 10a: The pipeline from pre-operative exam to template. 10b: This section describes the template design workstation: Joysticks, stereo viewing glasses, pushbuttons, and physical sliders provide more natural human interfaces than overloaded mouse controls.

To augment the interactive visualization of the vertebrae and the placement of tool paths, the workstation has recently been augmented with physical I/O devices including a 3D joystick, supplementing the overloaded mouse controls. A mouse is by definition a 2D input device, limiting its use for viewpoint control. Tactile coherence can be improved by the use of physical input devices.

Volren 6.1, a texture-based volume rendering system running on a dual 250 MHz CPU Onyx2 with dual Reality Graphics™ raster managers was modified into a surgical planning workstation enabling the modeling of objects through constructive solid geometry (CSG). Texture based volume rendering naturally combines clipping planes and polygonal objects in a simplified volume rendering pipeline. The hardware-accelerated graphics systems necessary to support these methods are available in PC cards today. Clip planes, polygonal models, and volume rendering combine to make a natural graphical interface for planning screw placement.

4.3 Results and Discussion

As a test of the technology and its precision, we selected a dry, dissected lumbar vertebrae and created a surgical plan for pedicle screw placement. Thin section CT scans (1mm apart and 1mm thick) of 5 individual dry lumbar vertebrae were obtained on a GE Genesis High Speed RP Scanner. A block was modeled to fit tightly to the posterior surface of the vertebrae. Cylinders, that would ultimately be the drill guides, were then modeled through the block. The positioning of the cylinders, or trajectory planning, was accomplished with the aid of clipping planes and interactive control of the volume rendering transfer functions. This assured the authors that the planned trajectory was through the isthmus and along the axis of the pedicle, as shown in Figure 12-11. The 3-D drill guide block with trajectories was then divided into 2-D slices and converted to DICOM files. The 2-D slices were imported into Mimics v.6.3 (Materialise) and converted to STL files. The STL files were then used to generate the tool paths for the Fused Deposition Modeler (FDM) 2000 (Stratasys).



a. b.

Figure 12-11. The template design, taken from the texture-based volume rendering based surgical planning workstation. Clipping planes, polygonal primitives, and volume data are easily combined using advanced graphics.

We have achieved frame rates on the order of 10 frames per second for interactive template design including rendering the medical volume. Drawing from experience with molecular modeling systems, physical I/O tools such as joysticks were added improving the intuitive feel of the workstation. Some overloading of the input devices still occurs, leading to occasional confusion. Stereo viewing does not appear to speed template design. The use of Open GL as a programming base significantly reduced software development costs and permitted the fast integration of CSG.

A drill guide was produced by the FDM 2000 with approximately 125.06 cm^3 of non-medical ABS plastic at a slice interval of 0.2540 cm. The block, as designed, had an intricate area reserved for the posterior elements of the chosen lumbar vertebra. This first attempt was flipped in the x-axis due to an image format discrepancy. A second template was produced, correcting the defect, and pedicle pilot holes were drilled into the dry vertebrae. A CT scan was conducted to verify the placement of the pilot holes (Figure 12-12). Physical templates transfer the power of surgical planning workstations to the operating room without the need for complex technology. Confidence in the path planning will increase accuracy, speed procedures and reduce patient radiation dose by decreasing fluoroscopic verification (Yoo, 2001b).

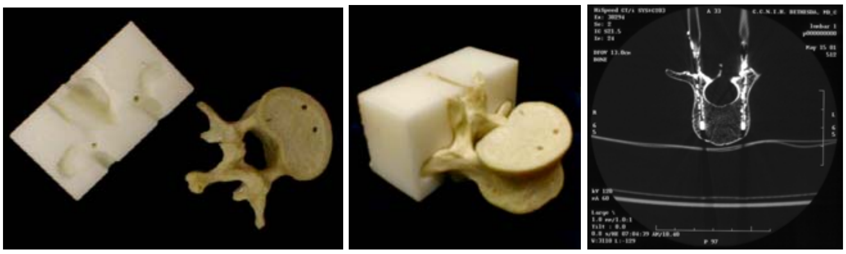


Figure 12-12. The prototype template and the dry spine test with a validating CT exam. (The pinholes in the top of the vertebrae are incidental, and leftover from the string connecting multiple vertebrae for its former use as an anatomy teaching tool.).

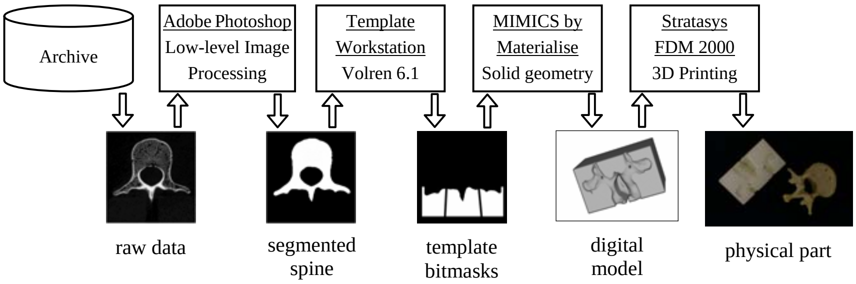


Figure 12-13. A 3D medical informatics pipeline using patient specific surgical instrumentation as a case study. The data transforms from raw image images to segmented objects (bitmasks), to designed shapes (embedded trajectories in mold bitmasks), to digital models (computer graphics models in STL format) to physical plastic parts manufactured with a rapid prototyping system. As the data is transformed, it is modified from raw images to physical instruments, encapsulating information in progressively higher-level abstractions.

The problems associated with designing and executing patient specific surgical instrumentation are easily cast as part of a 3D medical informatics data flow. Essentially, the idea of patient-specific surgical instrumentation in this example is the communication of information from a complex digital setting to precision surgical environment through a physical device. Intuitively, this means acquiring specific information about the patient’s anatomy, planning the trajectories of the pedicle screws, developing spatial relationships between the plan and the patient, and embedding that information in an instrument. Like other problems in 3D medical informatics, this can be seen to be a series of processes that refines information from raw data through abstractions such as positive and negative images of the spine to digital models of solid geometry and eventually to a device (See Figure 12-13). Beyond information retrieval, 3D medical informatics can play a vital and direct role in medical intervention.

5. GRAND CHALLENGES IN 3D MEDICAL INFORMATICS

What are the grand challenges in 3D medical informatics? Whenever asking such questions, it is useful to phrase the notion using three interrogatives: What? How? If? Taking these points in order, "*What* areas of medical practice and public health can we affect through 3D medical informatics?" 3D medical informatics can provide new frontiers in medical education in anatomy, physiology, molecular biology, and other disciplines. In addition, research in this area has already had a profound impact on emerging technologies in computer assisted surgical planning and image-guided interventions. The areas where 3D medical informatics may have its greatest influence is in the areas of computer-aided diagnosis in early detection and progressive tracking of chronic, degenerative diseases where the pathology has important expressions in time and spatial domains.

How can we influence these public health concerns? We can open entire search strategies for finding information based on visual data. New databases based on volumetric data collections may permit rapid disease identification and provide indices to other sources of textual and digital information. Many diseases are not characterized by their expression in a single point in time, but rather by the chronology of the changes in their shape or function. Spiral chest CT exams and MRI breast imaging are currently being considered as alternatives to traditional 2D chest X-rays and 2D mammography as screening tools for early cancer detection. 3D imaging will become commonplace in medical diagnosis and intervention. Detection and dynamic modeling of anatomy and physiology represents new medicine.

We can make this leap to 3D informatics only *if* new techniques and mathematics emerge to describe, index, and characterize complex, high-dimensional data. We do not yet have the visual linguistic tools to decompose image information into subject, object, predicate, modifier, or prepositional phrase. Even the visual alphabets of pixels and polygons are not sufficiently rich to support the power of images, much less 3D scans. What is required is the formation of a comprehensive foundation in image linguistics built upon reproducible object detection, computable shape descriptors, and common indexing metrics for organizing human thought represented in visual and volumetric data. Some of the specific challenges include:

- The development of new mathematical foundations for data representation, not based on polygons, voxels, or patches of curved surfaces. Shapes are not local collections of such atomic data elements, but rather the overall complex composition of them. Aggregating pixels or patches into shapes is akin to parsing language in a text-based system.

Mathematical formulations using implicit methods are emerging to describe anatomical structures through equations, but they lack sufficient maturity yet to influence the field (Yoo, 2001a).

- A scientifically grounded foundation in data decomposition, perceptual analysis, and ontology generation of complex multidimensional information built upon computable, reproducible image metrics. This challenge includes broad fundamental investigations into data segmentation and registration, image statistics, and image understanding to answer the need for repeatable, comparable methods for decomposing, parsing, and extracting semantic knowledge from images.
- Establishment of public repositories of medical volume data. Libraries and museum collections have been some of the greatest incubators for the taxonomies and ontologies necessary to index and catalog human knowledge. Photographs are less than 200 years old, and the enabling digital technologies for 3D medical informatics are younger still. However, our society has an opportunity to begin to explore visual communication at a fundamental level, and archival collections of complex data will help to accelerate the creation of new forms of reasoning about visual and volumetric information.

Linguistics and text-based informatics have strong historical roots, and the expression of human thought in language has descended and evolved through the ages. There are museums and libraries dedicated to collecting and understanding text. There is even a museum of the alphabet that celebrates the constellation of alphabets used worldwide. Visual and digital analogs to these institutions do not yet exist. Yet there is incontrovertible potential for creating visual lexicons, parsing high-dimensional data, and developing semantic understanding of complex data. There may come a time when the routine representation of information in human endeavors similarly includes and celebrates images and volume data.

6. CONCLUSION

3D medical informatics is a synthesis of medical image processing, visualization and computer graphics, modeling, and data storage and retrieval. This concept is built up of multiple strengths with extensive study in particular core areas. Like text-based informatics, visual information is refined through a variety of methods creating from raw data abstractions of greater and greater sophistication, permitting the collection, indexing and storage, display, and manipulation of complex data. The tools for this work are still rudimentary, but they have strong analogs in the text domain. New collections including complex spatial and temporal data will continue to challenge researchers to refine and invent methods for handling these issues, likely borrowing heavily from the linguistics and informatics communities. The future of this discipline is uncertain but bright with possibilities.

7. ACKNOWLEDGEMENTS

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REFERENCES

Ackerman, M.J. (1998). "The Visible Human Project," in *Proceedings of the IEEE*, 86(3),504-511.

Birnbaum, K., Schkommodau, E., Decker, N., Prescher, A., Klapper U., and Radermacher, K. (2001). "Computer-assisted Orthopedic Surgery with Individual Templates and Comparison to Conventional Operation Method," *Spine*, 26(4), (2001 Feb 15), 365-70.

Cabral, B., Cam, N., and Foran, J. (1994). "Accelerated Volume Rendering and Tomographic Reconstruction Using Texture Mapping Hardware," in *Proceedings of the 1994 Symposium on Volume Visualization* (Tysons Corner, Virginia), ACM Press, 91-98.

Castelli, V. and Bergman, L.D. (2002). *Image Databases: Search and Retrieval of Digital Imagery*, Wiley Interscience: New York.

Drebin, R., Carpenter, L., and Hanrahan, P. (1988). "Volume Rendering," *Computer Graphics* (Proceedings of ACM SIGGRAPH 88), 22(4), 65–74.

Funkhouser, T., Min, P., Kazhdan, M., Chen, J., Halderman, A., Dobkin, D., and Jacobs, D. (2003). "A Search Engine For 3D Models," *ACM Transactions on Graphics (TOG)*, 22(1) (January 2003), 83—105.

Hilaga, M., Shinagawa, Y., Kohmura, T., and Kunii. T.L. (2001). "Topology Matching for Fully Automatic Similarity Estimation of 3D Shapes," in *Proceedings of the ACM SIGGRAPH*, Los Angeles, CA, USA, 203-212.

Hillman, G.R., Tagare, H.D., Elder, K., Drobyshevski, A., Weller, D., and Würsig, B. (1998). "Shape Descriptors Computed from Photographs of Dolphin Dorsal Fins for Use as Database Indices," in *Proceedings of the IEEE Eng. Medicine Biology Society*.

Höhne, K.H., E*t al. (*2000). *Voxel-man 3D Navigator*, Springer: Berlin.

Jolesz, F. (1997). "Image-guided Procedures and the Operating Room of the Future," *Radiology*, 204, 601-612.

Kelemen, A., Szekely, G., and Gerig, G. (1999). "Elastic Model-based Segmentation of 3-D Neuroradiological Data Sets," *IEEE Trans. on Medical Imaging*, 18(10), 828-839.

Kikinis, R., Guttmann, CRG., Metcalf, D., Wells, W.M., Ettinger, G.J., Weiner, H.L., and Jolesz, F.A. (1999). "Quantitative Follow-up of Patients with Multiple Sclerosis Using MRI: Technical Aspects," *Journal of Magnetic Resonance Imaging*, 9(4), 519-530.

Kniss, J., Kindlmann, G., and Hansen, C. (2001). "Interactive Volume Rendering Using Multi-dimensional Transfer Functions and Direct Manipulation Widgets," in *Proceedings IEEE Visualization 2001).* (October 2001), 255-262.

Leiman, D.A, Twose, C., Lee, T.Y.H, Fletcher, A., and Yoo, T.S. (2003). "Rendering an Archive in Three Dimensions," *Medical Imaging 2003, Visualization. Image Guided Processing and Display* (February 16-21, 2003), San Diego, CA, Proc. SPIE, 5029, 9-17.

Levoy. M. (1988). "Display of Surfaces from Volume Data," *IEEE Computer Graphics and Applications*, 8(3)(May 1988), 29–37.

Lorensen, W.E., and Cline, H. (1987). "Marching Cubes: A High Resolution 3D Surface Construction Algorithm," in *Computer Graphics* (Proc. SIGGRAPH 87*)*, 21, 163-169.

McCormick, B., DeFanti, T., and Brown, M., (*eds.*), 1987. "Visualization in Scientific Computing," ACM SIGGRAPH, New York.

Shenton, M.E., Gerig, G., McCarley, R.W. Szekely, G., and Kikinis, R. (2002). "Amygdala-hippocampus Shape Differences in Schizophrenia: The application of 3D Shape Models to Volumetric MR Data," *Psychiatry Research Neuroimaging*, 115, 15-35.

Smeulders, A.W.M, Worring, M., Santini, S., Gupta, A., and Jain, R. (2000). "Content-based Image Retrieval: The End of the Early Years," *IEEE Trans. Pattern Anal. Machine Intell.* 22(12), 1349–1380.

Szekely, G., Kelemen, A., Brechbuehler, Ch. and Gerig, G. (1996). "Segmentation of 3D Objects from MRI Volume Data Using Constrained Elastic Deformations of Flexible Fourier Surface Models," *Medical Image Analysis* (*MEDIA),* 1(1)(March 1996), 19-34.

Tagare, H.D., Vos, F., Jaffe, C.C., and Duncan, J.S. (1995). "Arrangement: A Spatial Relation Between Parts for Evaluating Similarity of Tomographic Section," *IEEE Trans. Pattern Anal. Machine Intell. (1*7(9), 880–893.

Tagare, H.D., Jaffe, C.C., and Duncan, J.S. (1997). "Medical Image Databases: A Content-based Retrieval Approach," *Journal of the American Medical Informatics Association.*, 4(3), 184–198.

Westover, L. (1989) "Interactive Volume Rendering," in *Proceedings of Volume Visualization Workshop* Department of Computer Science, University of North Carolina, Chapel Hill, NC., May 18-19, Pp. 9-16.

Yoo, T.S., Neumann, U., Fuchs, H., Pizer, S., Cullip, T., Rhoades, J., and Whitaker, R. (1992). "Direct Visualization of Volume Data," *IEEE Computer Graphics and Applications,"* 12(4)(July 1992), 63-71.

Yoo, T.S., Morse, B., Subramanian, K.R., Rheingans, P., and Ackerman, M.J. (2001a). "Anatomic Modeling Ffom Unstructured Samples Using Variational Implicit Surfaces," in *Studies in Health Technology and Informatics,* 81 (*Proceedings of Medicine Meets Virtual Reality 2001*. J. D. Westwood, *et al., eds*.), Amsterdam, IOS Press: 594-600.

Yoo, T.S., Morris, J., Chen, D.T., Burgess, J., and Richardson, A.C. (2001b). "Template Guided Intervention: Interactive Visualization and Design for Medical Fused Deposition Models," in *Proceedings of the Workshop Interactive Medical Image Visualization and Analysis* (18 October 2001, Utrecht, the Netherlands), 45-48.

Yoo, T.S. and Ackerman, M.J. (2004). "Engineering a Scientific Rendezvous: The Insight Toolkit for Medical Image Processing and Visualization," *Communications of the ACM*.

SUGGESTED READINGS

Christopher Johnson and Charles Hansen, *eds*. 2004. *The Visualization Handbook*. Elsevier, Academic Press.

Visualization involves constructing graphical interfaces that enable humans to understand complex data sets; it helps humans overcome their natural limitations in terms of extracting knowledge from the massive volumes of data that are now routinely connected. This book is a new resource on advanced visualization edited by two of the best known people in the world on the subject with chapters contributed by authoritative experts.

Vittorio Castelli and Larwence D. Bergman. 2002. *Image Databases: Search and Retrieval of Digital Imagery*, Wiley Interscience: New York.
This book is a broad introduction to the topic of image databases with in-depth analyses provided by some of the leading researchers in the field. It includes an introduction on the basics of image databases and the sources of such data as well as the technologies to store, compress, transmit and search large image-data collections.

Arnold W. M. Smeulders, Marcel Worring, Simone Santini, Amarnath Gupta, and Ramesh Jain. Content-based image retrieval: the end of the early years. *IEEE Trans. PAMI*, 22 - 12:1349 -- 1380, 2000.
This is an essential review of over 200 peer-reviewed publications on the topic of content-based image retrieval. The article describes methodologies and motivations for pursuing this domain and the intersection of this area with other parts of informatics, engineering, and science.

ONLINE RESOURCES

The National Library of Medicine's Visible Human Project™ (NLM VHP) has sponsored the collection and distribution of anatomical data of two human subjects. In addition, the NLM VHP has also created and managed the program to create the Insight Toolkit (ITK), the public open-source software collection for high-dimensional image segmentation and registration. The URL for these projects are respectively:
http://www.nlm.nih.gov/research/visible/visible_human.html
http://www.itk.org

The Princeton Shape Retrieval and Analysis Group has a web site for their 3D Model Search Engine. This system permits the indexing and retrieval of thousands of 3D computer graphics models based on query by sketch. You can try your hand at sketching and retrieving models at:
http://shape.cs.princeton.edu/search.html

The Voxel-man group at the University of Hamburg has published digital collections of Quicktime-VR representations of human anatomy linking of ontologies/taxonomies with image data in multiple dimensions. These CD sets show what is possible today using modern technologies in medical scanning, image generation, and careful presentation of digital anatomy resources. These CD sets are published by Springer and are available from bookstores and online vendors. Look for:
Höhne, K.H., *et al.,* 2000, Voxel-man 3D Navigator

QUESTIONS FOR DISCUSSION

1. It is said that, "A picture is worth a thousand words." Compare the notions of text-based informatics and image-based informatics. What are

the similarities? What are the salient differences? What foundations exist in text-based informatics that are missing among images? What areas of fundamental cognitive and information science research does this suggest? Discuss.

2. How do images play a role in society? How does the growth of volume data affect medicine and other disciplines such as meteorology, seismology, and oceanography? What burdens are these growing computational needs going to place on medical informatics? What opportunities? Discuss.