Graphics, Vision, and Visualization in Medical Imaging:

A State of the Art Report

Norberto Ezquerra[1], Isabel Navazo[2], Tahía Infantes Morris[1], and Eva Monclús[2]

[1]Graphics, Visualization & Usability Center
College of Computing
Georgia Tech, Atlanta, GA, USA

[2]Instituto de Robotica e Informática Industrial
Universidad Politécnica de Cataluña
Barcelona, Spain

norberto@cc.gatech.edu, tahia@cc.gatech.edu

isabel@iri.upc.es, emonclus@iri.upc.es

ABSTRACT

The field of medical imaging has significantly changed over the years, becoming both an integral part of health care and an increasingly important area of research spanning many disciplines. As the title of this paper suggests, one interesting result of this evolutionary process has been the fusion of traditionally disjointed yet highly interrelated areas: from computer vision and image processing, through graphics and visualization, to the integration of creative immersion and robotics-based mechanisms for interactively manipulating the information. As a result of these innovations, medical imaging has continued to re-invent itself, fundamentally changing the ways in which we see, communicate about, learn from, and interact with, medical information.

With this in mind, the purpose of this state-of-the-art (STAR) report is two-fold. On one hand, the aim is to provide a brief summary of some of the salient methods, results, and potentially powerful trends that currently describe the field. On the other hand, the goal is to outline some of the remaining challenges as well as the possible opportunities. Clearly, the field is far too broad and complex for a single article to adequately reflect the technical depth and extraordinary diversity of even a small portion of these topics. Thus, without any claim at completeness, the emphasis will be placed on highlighting selected frontier research activities and applications, focussing on aspects related to vision, graphics and visualization from an interpretive (rather than tutorial) perspective.

In addition to these discussions, a list of URLs of some of the groups actively engaged in medical imaging research is also included. The overall objective is therefore to provide a "snap shot" of the field through a brief summary that will hopefully serve as a useful source of information for those wanting to learn more about the field, and, for those actively engaged in the field, a timely -and possibly inspirational- reference.

Keywords: Medical imaging; graphics; medical graphics; vision; 3D imaging; medical computing.

1. INTRODUCTION

Since Roentgen's landmark discovery of X-rays in 1895, the field of medical imaging has advanced rapidly, drastically and continually, emerging both as an integral part of health care as well as a focus of research activity. The evolution of the field has been the result of several converging forces. One influential factor has been the emergence of increasingly powerful hardware and software systems, which, spurred by accompanying reductions in costs and functionality, have resulted in wider accessibility and the gradual creation of some standards [Sof98; Sha98]. For instance, it has been pointed out that the capabilities of most advanced graphics workstations built as recently as 1990 are comparable to (if not lesser powerful

This work was supported in part by grant R29 LM04692 from the National Library of Medicine.

Published by the Eurographics Association ISSN 1017-4656

than) those of off-the-shelf consumer products of today, such as Nintendo's Ultra 64 video game [Sof98].

Innovations in image acquisition technologies have also taken place, including modalities capable of capturing the dynamics of heart muscle motion or brain function. The flexibility of image acquisition systems, coupled with increased computational power, have enabled researchers to contemplate a diversity of new medical applications. One interesting result of these changes has been the fusion of largely disconnected yet interrelated areas: from computer vision and image processing, through graphics and visualization, to the integration of creative immersion and robotics-based mechanisms for interactively manipulating the information. An example of this convergence of disciplines is illustrated in Figure 1, which shows a simulation and rehearsal environment incorporating deformable anatomical models and force-feedback interaction, developed by researchers at INRIA [Aya97; Aya98; Cot96; Cot99a; Cot99b] and discussed later in the paper.

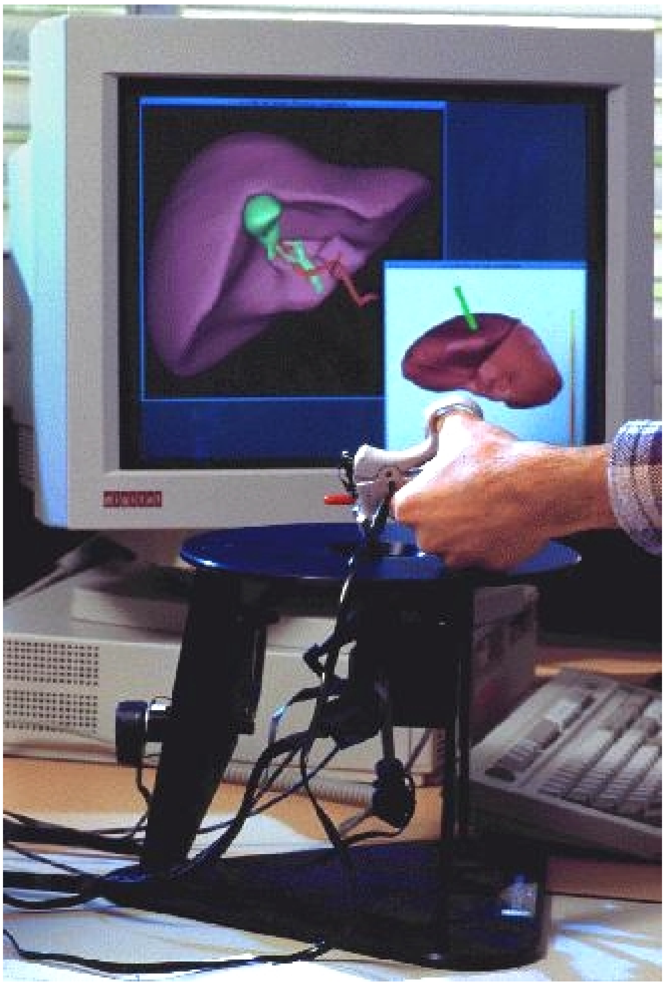


FIGURE 1 Simulation of a surgical operation on the liver. Interaction with the deformable model is through a force feedback system. Courtesy of Nicholas Ayache, Stephane Cotin, Hervé Delingette, INRIA, France [Aya97; Cot96; Co99a; Cot99b; Del98].

As the field has evolved, so has its intellectual reach. Traditionally disjointed yet interrelated areas are frequently used in order to address emerging technical issues and challenges. An overview of some of the computational tasks that can generally be involved in the medical imaging process is shown in Figure 2, which will serve as a roadmap for our discussions. As suggested in this figure, the sequence of steps associated with the acquisition and subsequent utilization of medical imagery has changed significantly over the years, evolving from a task primarily based on the visual inspection of 3D structure projected onto 2D planes (such as film) to a process involving sophisticated methods and tools that incorporate a diversity of technologies and which can support different applications.

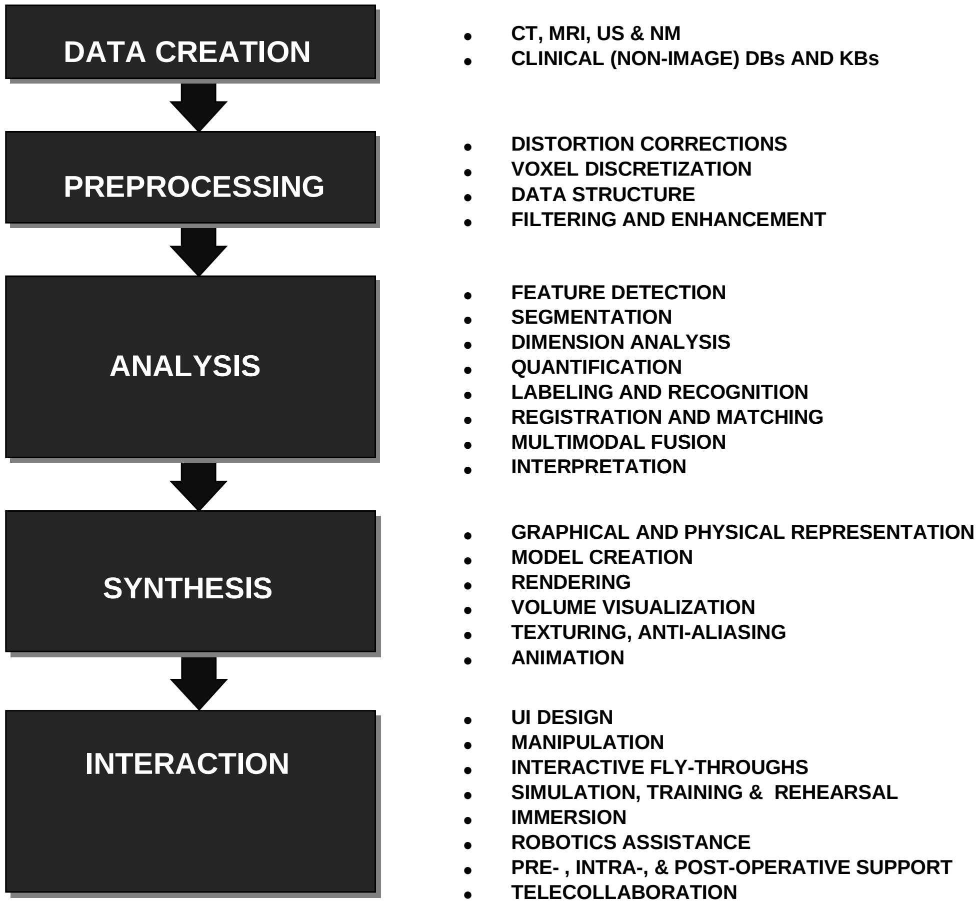


FIGURE 2 Sequences of stages in Medical Imaging.

Interestingly, this sequence -especially when viewed from top to bottom in Figure 2- to some degree captures the evolution of the field itself: from the initial invention or development of an imaging mechanism to the design of increasingly interactive environments. As suggested in the figure, the sequence generally consists of:

(i) **data acquisition and preprocessing**, including image filtering, volume discretization, and other preliminary data preparation steps. For brevity, this initial stage might be viewed as the creation or genesis of a useful dataset that would facilitate subsequent processing.

(ii) **analysis**, aimed at extracting relevant information from the data given a specific application, including feature extraction and characterization, multimodal image fusion, and interpretation.

(iii) **synthesis**, devoted to the creation of visual and manipulable representations of the extracted information, including rendering and display, and building mechanisms to support interaction.

(iv) **interaction**, centered on providing diverse modes of interaction that facilitate users’ goals and tasks, including visual, tactile, aural, and force-feedback and remote interactions.

The order in which the various stages shown are invoked is generally non-linear and possibly cyclical. In addition, the types of user can also vary to include physicians, researchers, clinical technicians, students or trainees, and manufacturers, among others. It should also be stated (rather emphatically) that the design of the user interface (UI) or interaction mechanism is perhaps the most important component in the process.

With this in mind, the present paper attempts to provide a "snap shot" of the field, highlighting some of the representative frontier research activities and selected illustrative applications

Published by the Eurographics Association ISSN 1017-4656

without any claim at completeness. In closing the introduction, a few observations ought to be made. Firstly, we acknowledge the contributions of many colleagues who provided valuable and timely information for the preparation of this document; a list of their names (and URLs) precedes the bibliography. Secondly, this STAR report will hopefully inspire others to generate subsequent, more complete and improved versions. Thirdly, the discussions are placed in the context of creative research ideas that, while promising and exciting, nonetheless are largely investigative in nature, underlining the need for extensive validation and integration into the clinical environment in order to demonstrate their overall clinical utility.

2. DATA CREATION

To construct useful models that can be quantified, visualized and manipulated, it is first necessary to acquire image data, and, as appropriate, preprocess this information. Table 1 summarizes the basic acquisition modalities of X-ray, nuclear medicine (NM), magnetic resonance (MR), and ultrasound (US) imaging. The theoretical underpinnings related to these modalities, as well as related engineering and instrumentational issues, are amply documented in the literature [Rho97; Udu91; Sty91; Shu92].

MODALITY	BASIC CHARACTERISTICS	VARIATIONS	RELATIVE DATA SIZE (MB/Image)	(MB/Exam)
X-RAY	• Transmission Modality • Measures Beam Attenuation • Indicates Relative Tissue Structure & Density • Ionizing EM Radiation • Used in Diagnosis, Therapy & Monitoring	• Planar Projection Xray • CT • Spiral CT • Angiography	0.8 0.52 0.8	04 13 32
NUCLEAR MEDICINE	• Emission Modality • Measures Radioactive Counts • Indicates Metabolic Uptake or Physiologic Process • Ionizing EM Radiation • Used in Dx, Rx & Monitoring	• PET • SPECT • Gated	0.13	0.8
ULTRASOUND	• Transmission Modality • Measures Changes in Characteristic Impedance • Indicates Relative Change in Structure & Motion • Non-Ionizing US Waves	• Planar Projection US • Doppler	0.3	11
MAGNETIC RESONANCE	• Transmission / Emission • Measures Currents Induced by Nuclear Magnetic Moments • Indicates Molecular Structure & Dynamics of Tissue • Non-Ionizing EM Radiation	• 2D Slice Acquisition • MRA • t-MRI • f-MRI	0.5	16

TABLE 1 Image Processing Sequence

Computed tomography (CT) was introduced in the 1970s, allowing the acquisition of tomographic slices (or cross sectional views) that can be "stacked" contiguously to produce a data volume. More recently, the introduction of spiral CT has enabled continuous acquisition while the patient is automatically advanced across the CT image plane. Angiography, using both X-ray and MR imaging, provides vasculature information. Nuclear medicine (SPECT and PET) images measure functional or physiological processes, such as the distribution of blood flow in the heart muscle or brain metabolism as a function of neurological stimuli. Another innovation is functional MRI (f-MRI), which generates images that are indicative of functional activity within small time intervals [Bis96; Bull96; Xio96]. A recent advance is the generation of tagged MR images, wherein subvolumes of tissue are magnetized along planes separated by several millimeters such that these planes appear as "tag" lines in the 2D images [Pri92; Par95; Ami98; You95]. By successively acquiring a series of tagged images, possible distortions of the tissue become visible as displacements or distortions of these tag lines. An example of tagged-MR images is given in Figure 3 [Pri92].

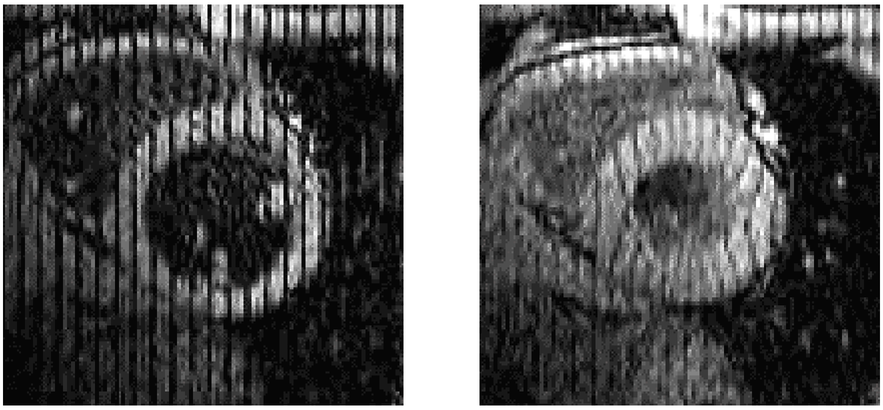


FIGURE 3 Tagged MRI of a short axis plane of the heart. Courtesy of Jerry L. Prince, IACL Johns Hopkins University [Pri92; Den95].

Potentially significant advances have recently been made is in the field of three-dimensional ultrasound [Cai99; Pra98; She98; Ste94] and also intravascular ultrasound (IVUS) [Leu95]. An illustrative example is the work carried out by Sakas and his group at the Fraunhofer Institute in Darmstadt, Germany. In a project spanning several imaging applications called InViVo, this group is exploring methods for improving the quality, reliability, speed and delivery costs associated with 3D ultrasound [Sak98; Sak97]. Multi-resolution interactive filtering techniques are used to enhance the images, while semiautomatic segmentation is used for extracting structures of interest [Wal95]. This is followed by surface reconstruction to create 3D surface representations of relatively large organs or, in the case of prenatal assessment, the entire fetus [Sta89; Sak97]. The diagnostic value of the method is three-fold: as a method for detecting small regularities of the fetal surface, by providing a better overall impression of the fetus compared to 2D images, and by offering the mother a more intuitive impression of the unborn. Figure 4 shows an example of the US imagery that is currently possible with this approach [Sak98].

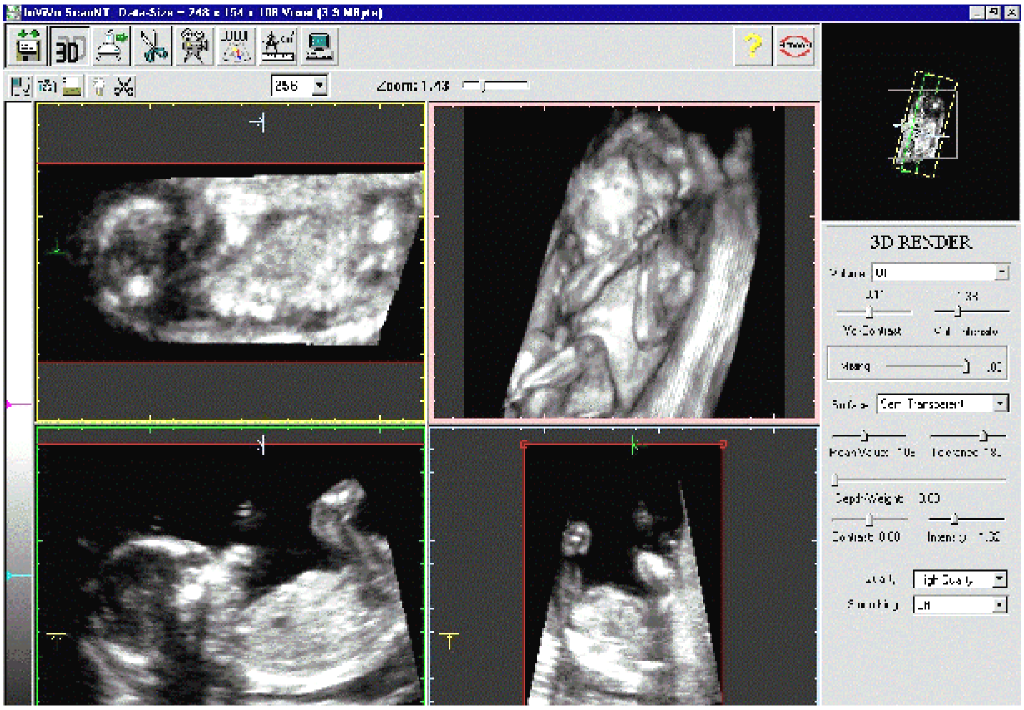


FIGURE 4 Interface of Invivo-ScanNT displaying a semi-transparent volume rendering of a foetus (notice the fingers). Invivo-ScanNT provides a powerful visualization software for generating 3D images within a few seconds on low-cost computers under routine clinical conditions. Courtesy of Georgios Sakas, Fraunhofer IGD/Germany [SAK97; SAK98].

Published by the Eurographics Association ISSN 1017-4656

Other imaging modalities, such as thermography, confocal microscopy and magnetoence-phallography [Sak97; Tog96], have become increasingly important since they can offer different informational content and/or provide data at very different scales. One interesting example is the work of Streicher, Weninger and collaborators, who are creating visualizations of sub-microscopic specimens [Wen98]. In their work, methods are being developed to perform both 3D reconstruction and visualization of histological sections using automated congruencing of histological serial sections, as well as 3D reconstruction of morphological structures from physically sectioned, paraffin embedded specimens at sub-microscopic resolution. An example of some of their work is illustrated in Figure 5, which shows the results of a new episcopic method for rapid 3D reconstruction applied to embryology. As suggested by this example, the visualization and interaction methods currently available are generally applicable to most modalities. These innovations point to some of the most promising current trends in medical image acquisition.

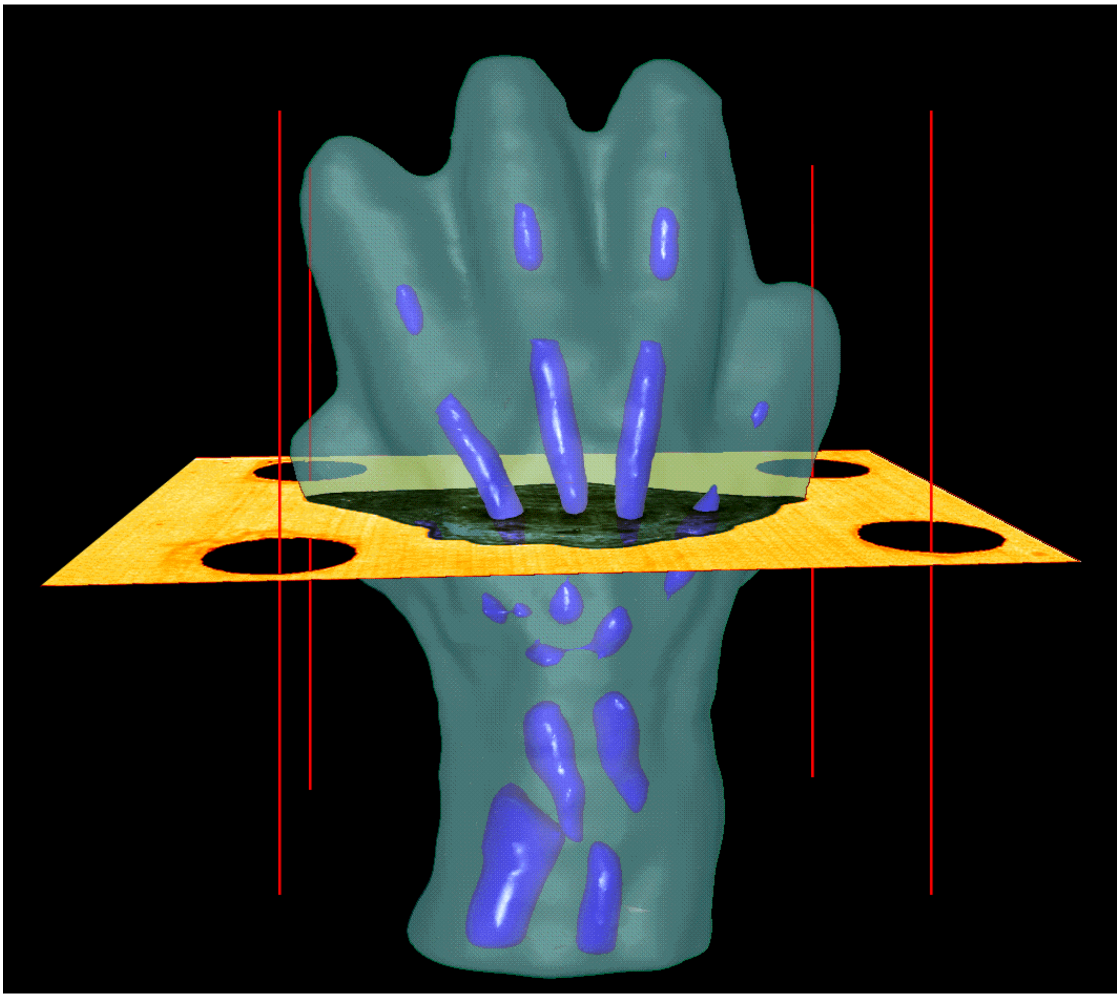


FIGURE 5 3D-reconstruction of the surface and the skeletal rudiments of the hind limb of a Theiler stage 22 mouse embryo from serial histological sections. The vertical lines stand for the axes of drill holes that serve as external markers for automatic congruencing. Courtesy of Johannes Streicher, University of Vienna [Wen97; Wen98].

Other advances have occurred, such as the trend toward open architectures and incorporation of off-the-shelf (OTS) tools and software [Nei93; Sof98] as well as dedicated graphics hardware development [Cub4ONL; Ake93; Fuc89], and the emergence of some standards such as the DICOM guidelines [NEM98ONL].

Once information is acquired (possibly using several modalities), a series of 2D slices or cross

Published by the Eurographics Association ISSN 1017-4656

sections through tissue is generated. At this point, the data set needs to undergo a number of additional preprocessing steps, including correcting for image distortions [Sty91; Shu92], and steps designed to discretize (or voxelize) the volume [Udu91] using a variety of well established methods [Kau91; Kau94; Mar94; Bar94a]. In addition to these steps, the imagery is frequently processed to improve the signal-to-noise (SNR) ratio [Bah90; Bal82; Har92] and enhance certain signal characteristics [Ros82; Opp75; Jai89]. Some datasets may require special preprocessing due to the acquisition method employed. An example is US, to address -and take advantage of- the characteristics of speckle (such as its texture properties) [Cze98; Gia99; Roh97]. Additionally, 3D US data acquisition is sometimes achieved through methods that result in asymmetrical distributions of data points [Tre98a], for which newly developed preprocessing methods have recently been developed [Gia99; Jac99; Tre98a]. Other preprocessing steps include constructing binary-valued or multiply-valued (grey-valued) volumetric representations [Dre88; Lev88; Che85] and related data representations such as octrees [Lau91; Fol90; Wat93]. Additional information can be created or introduced, such as other images or reference models, non-image information derived from clinical DBs or knowledge bases [Ezq99; Sak97; Höh95], and/or links to related hypermedia or multimedia sources [Tre96].

3. ANALYSIS

Once the desired DBs and KBs have been created, the emphasis is placed on the analysis of all the available information, with the overall goal of extracting certain features that are of interest and subsequently characterizing and interpreting these features. Implicit in this process, and central to it, is the concept of features: first defining a feature or a set of features, and then finding them in the scene. This general concept of finding, extracting, and characterizing features is called **segmentation**. Several definitions of segmentation have been proposed [Jai89; Mar80a; Udu91], all of which are equally valid. Therein lies one of the main difficulties with this task: segmentation is fundamentally an ill posed problem, at times resembling a combination of goals, methods, and ideas. From a scientific perspective, there are no "first principles" to invoke in segmentation, such as energy conservation in physics, for example. However, a number of techniques have been developed, usually classified as point-, feature-, or region-based operations guided by higher level model- or knowledge based methods [Bal82; Har92; Ros82]. Some of the latest segmentation techniques can be sampled in [MIC98].

Among well established segmentation approaches, connectionist techniques (i.e., methods based on artificial neural networks [Win92; Koh88]) have been used to segment 2D images [Har93; Che91], to interpret 3D cardiovascular SPECT imagery [Ezq92] and to predict myocardial function [deB96a]. Another family of approaches draws from mathematical morphology (MM) [Ser82; Ser88; Ron91]. This set-theoretical approach has been successfully used, for instance, to segment brain from non-brain matter (including other soft tissues as well as the skull) in 3D MRI datasets in a fully automated fashion [Mad96], and in 2D MRI brain imagery [Bru93]; it has also been used to interactively segment tissue in MR and CT imagery [Höh92b; Sch92a]. An extension of the set-theoretical formulation is the notion of "fuzzy" set-membership and fuzzy connectivity methods. As pointed out in the recent work of J. Udupa and collaborators [Udu97a; Udu97b], the basic idea is that images are the result of a discrete, noisy and possibly non-linear acquisition processes, and that the objects sampled through this process (i.e., organ tissue) are inherently heterogeneous in composition. Fuzzy approaches have been proposed for some time to estimate, for instance, the percentages of different materials contained in voxels [Dre88] and to describe relationships between anatomical structures in MRI [Men92].

In the fuzzy segmentation approach currently being developed by Udupa et al., both the material composition as well as their connectivity (or "connectedness") are handled using fuzzy-set theoretical methods [Udu96]. The underlying fuzzy-membership functions are pair-wise relationships based on proximity, intensity, and intensity-based properties, while the computational challenge associated with examining all pair-wise combinations in an image is handled through innovative dynamic programming methods. An illustration of the results that can be obtained from these techniques is shown in Figure 6, which compares the results obtained using different segmentation methods. As shown in this figure, the image on the right (corresponding to the fuzzy-membership segmentation results) reveals finer muscle-tissue detail that is not easily visible with the other method. These fuzzy-connectivity algorithms have been implemented and validated in large numbers of cases involving segmentation problems related to multiple sclerosis applications [Sam97; Udu97b], showing the viability of the approach.

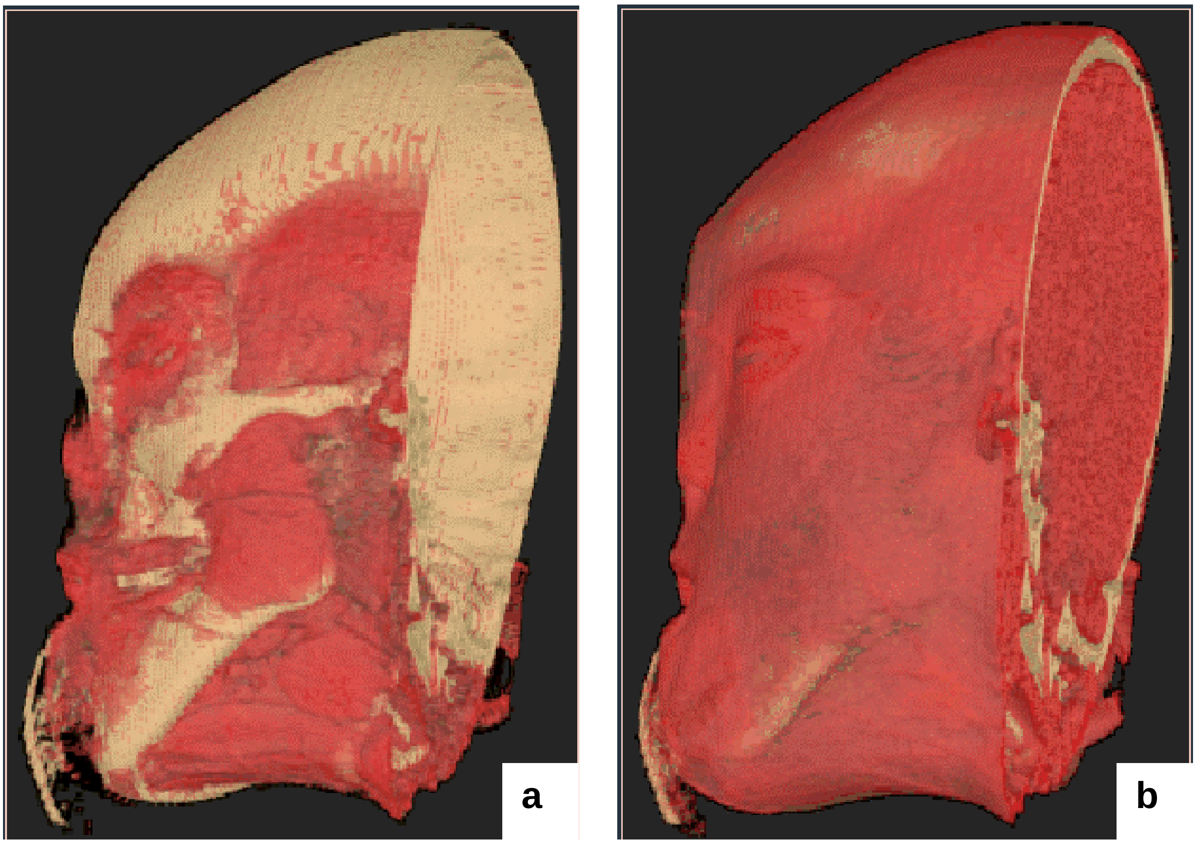


FIGURE 6 Renditions of two fuzzy objects derived from craniomaxillofacial CT. (a) volume rendition of bone and soft tissues (b) volume rendition obtained after the bone and muscles each have been identified as a fuzzy connected object. The skin has been peeled away since it is not very strongly connected to muscles. Courtesy of J.K.Udupa, U. Penn [Udu96; Sam97; Udu97A; Udu97B].

Another potentially powerful type of approach has theoretical underpinnings in discrete combinatorial topology [Vor07; Del34; Ale56], a framework concerned with mathematical descriptions of shape and topological characteristics and operations (including holes, tunnels, gaps, simplicial complexes, alpha shapes, skeletonization, etc.) [Ed94; Men75; Hen79; Cox73]. Methods based on discrete combinatorial topology have been applied to medical imaging problems, as reported in [Kal91; Lee93; Udu94a; Her93; Her92b; Boi85]. One recent application demonstrated the ability of the approach to extract patient-specific myocardial mass shape directly from 3D perfusion SPECT imagery to create a polyhedral representation [Ken96]. Another recent contribution, by Montagnat and Delingette [Mon98; Del98], uses simplex meshes to construct surfaces, as explained later in the context of modeling. In a related line of work, Vemuri and collaborators combine topological concepts with splines [Mal95].

The concept of active contours is also used significantly in current research. Introduced in the seminal papers by Terzopoulos, Kass and Witkin [Ter87; Kas87a; Kas87b], these active contours or "snakes" are splines that deform iteratively in order to adapt to image features, thereby resembling a hypothetical snake that wiggles in the image space until an adequate "final shape" is found [Men93]. The deformations are effected by a minimization process that takes into account two types of "forces" or influences: an internal force that represents the contour's elasticity and flexibility characteristics (typically expressed as functionals of first- and second-order derivatives), and an external force that represents the features of interest in the image (expressed, for example, as a functional of the gradient of the image). The approach resembles energy-minimization process in physics, in that the contour seeks to find minima. The commonly used framework is cast as a set of differential equations in an Euler-Lagrange formulation of the action integral (Hamilton's principle), well established in classical dynamics. Terzopoulos, and later McInerney and others, further explored, extended and applied the concept of active contours in medical imaging to such

Published by the Eurographics Association ISSN 1017-4656

issues as image analysis, segmentation, 3D surface creation, and non-rigid 3D body deformations [Nas94a], in some cases partially addressing some of the aforementioned shortcomings [Sin98; McI95b; Ter93; Ter92; Ter91].

A generalization of this concept, where dynamic models are combined with other methods, is an area of significant interest and activity in recent years. Along these lines, the issue of dealing with different topologies within a dynamic modeling framework has been recently examined [McI99; McI97]. Vemuri and collaborators have proposed a topology-independent shape modeling method that uses geometric curve or surface evolution combined with active contours [Mal95]. To achieve topology-independent shape modeling and segmentation, a curve/surface evolves as a function of its local curvature. When implemented in a level-set framework, the surface embedding the lower-dimensional curve is evolved, allowing the curve's position to be determined at any point during the evolution by simply finding the level-set of the embedding surface. The level sets need not be simply connected, thus permitting varied topologies. By making the evolving curve/surface sensitive to the local maxima in the image gradients, the desired shape boundaries of all shape "candidates" in a dataset may be recovered. This is akin to shrink-wrapping the shapes (objects) in an image or a scene, and may be viewed as geometric active models.

In related work, Prince and collaborators [Xu98a; Xu98b] consider the diffusion of a vector field of an image. The basic idea is to create a vector field that "points" in particular directions to guide the active contour minimization process. In this approach, the diffusion of an underlying vector field is computed, such as the gradient of an edge map, thus acting as an external "force" field related to image features (in this case, the gradient). The resulting hyperbolic differential equations are solved iteratively. The approach may improve the convergence to boundary concavities by providing an "inward flow" to influence the motion of the active contours. An example of the approach is given in Figure 7. In another extension of the active contour formalism, proposed by Pham and Prince [Pha99], the dynamic model is combined with fuzzy set theoretic concepts to address the problem of image inhomogeneities, such as brightness variations in photomicroscopy or partial-volume effects in MRI. These inhomogeneities are modeled with a smoothly varying gain field and combined with the fuzzy c-means algorithm.

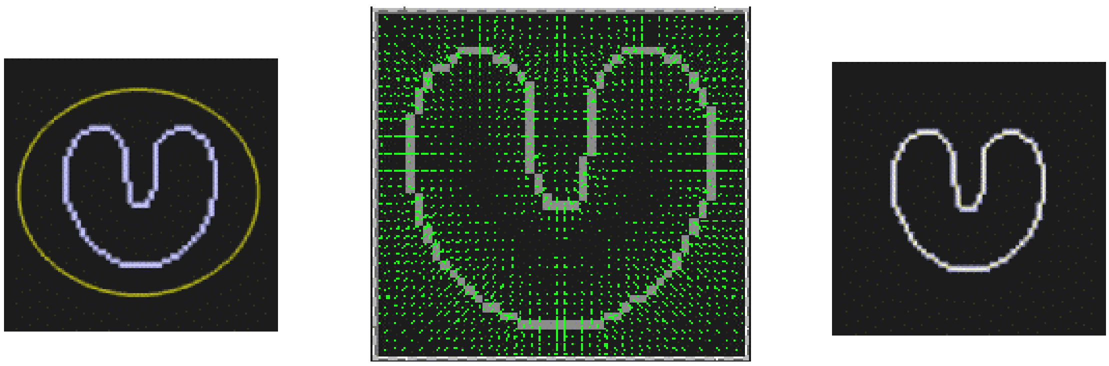


FIGURE 7 Results of a new snake algorithm based on gradient vector flow (GVF). "GVF Snakes" have been shown to solve two key issues concerning snakes: the problem that snakes cannot move toward objects that are too far away and secondly, the problem that snakes cannot move into boundary concavities or indentations (such as the top of the character U). Courtesy of Jerry L. Prince, IACL-JHU [Xu97; Xu98a; Xu98b].

An important aspect of segmentation is motion, when it becomes important to account for, or perhaps even focus on, the spatial displacements or the time evolution of structures and processes [McI93]. Many of the previously discussed approaches, including active contours or active surfaces, geometric active models, neural networks, pattern recognition methods, or combinations of these approaches, have extensively been used to study motion. For instance, in an early application of snakes [Hyc92], active contours were used to first define the center line of a coronary vessel segment in one frame of a ciné sequence, and then used the contour resulting from this frame as an initial starting place to detect the vasculature midline in a subsequent frame, repeating this process to successfully track an entire vessel as it moved in the temporal sequence. In other work, 4D cardiovascular processes have provided a useful setting in which to explore various models of dynamics [Dun95]. For instance, tracking of the left ventricle (LV) using superquadrics has been explored in [Bar94b], while motion estimation has been studied by several investigators using spatially constrained velocities [Mey95], shaped descriptors [Dun91], volumetrically deformable models [Par95], and B-surface reconstruction [Ami98]. One of the most active areas of research is the study of motion using MR and US data, such as tagged-MR image sequence data techniques [You95; Pri92; Pap98; Par95], including left-ventricular [Par95] and right-ventricular [Hab98] motion analysis, and interactive cine-3D segmentation methods [Pap98]. Motion analysis also plays an important role in US data segmentation and analysis [Glo99a; She98; Sak97].

Other approaches employ region-growing techniques, connected-component analysis, the computation of discontinuities [Can85; Der87; Mar80b; Bom90] or consider reaction-diffusion and anisotropic diffusion equations [Per87; Tek95; Ger92], which can be combined together and/or with preciously cited techniques. Examples include the extraction of myocardial mass from 3D SPECT imagery [Mul95], and the interactive segmentation approach reported in [Höh92b; Sch92a]. Spectral analysis methods continue to be employed to study, for instance, image harmonics [Cai99; Dun95], phase information in US imaging [Mul98; Jac99], and texture properties that would permit the decorrelation of selected signals from others [Wu90]. Other transformations include fractal decomposition [Lev92] and the wavelet tranform [Mal98; Aus92; Mal89; Don94; Fan96]. Along these lines, Lai and Vemuri have developed a computationally efficient algorithm for reconstructing signals in noisy scenes using a "preconditioning" method [Lai97]. They consider the optimization process associated with geometric active contours/surfaces [Mal95], which results in elliptic partial differential equations. The preconditioning is achieved using a wavelet-basis approximation of the spectral properties of the smoothness constraints imposed on the geometric active contours/surfaces. Another recent idea is the expansion of temporal data in terms of a family of basis functions called Brushlets [Aus92; Mey97], a decomposition into patterns of oriented textures that can be viewed as distinctive "brush strokes" of particular dimensions, an approach that may prove useful in separating noise from signal characteristics in such applications as US imaging [Mul98; Jac99].

Multiscale representations are also widely used to study details at different levels of resolution. Applications include vessel enhancement [Hoo98; Kol95], image enhancement [Fan96], edge and ridge detection [Lin98a; Lin98b], curvilinear structure segmentation [Sat97a; Sat98a; Sat98b], line segmentation with width estimation [Lor97], and symmetry considerations in terms of medial axes [Mor93]. Watershed-based approaches [Vin91; Gau93] are currently being applied to find ridges and valleys [Lin98b; Mad93; Gon91; Piz90], to detect vascular structure [Obr94; Liu93; Ron89], and have been applied to angiographic cine sequences, MRA, biplane angiography, and other imagery [Dui99; Lor97; Mad96].

It is possible to guide the segmentation algorithm, or improve the segmentation results, by invoking some type of domain knowledge, including model-based [Gri89; Lam88] and knowledge-based [Buc84; Cha85; Nat91; Win92] approaches. Model-based applications include anatomical models used for brain image segmentation and surgical planning [Kik96], segmentation using probabilistic spatial distributions of various structures obtained from 22 MRI studies [Ata95], and a combined model- and knowledge-based method for segmenting 3D myocardial mass [Ezq96a], and for segmenting and labeling arteries [OBr94; Ezq98].

The idea of matching two sets of points is also an important part of analysis [Van93b; Cov91; Lam88]. Landmark-based matching, wherein the matching is done by identifying corresponding landmarks in both sets, is commonly used in medical imaging. A specific example of landmark-based matching arises in the case of stereotaxy, which are fiducial markers are placed on the skull or obtained by placing the patient's head into a frame that provides the spatial reference. In this manner, a 3D model (created using MR and CT patient-specific data) can serve as a 3D roadmap with which to precisely determine the exact position of lesions and landmarks for subsequent matching [Kee96; Mol98]. Non-rigid transformations (or elastic matching) [Bes92; Ben94; Bac83] have also become widely used in medical imaging. Examples include spline interpolation or approximation [Roh98; Boo89] and surface-based matching methods [Sze96; Tho96]. Differential geometrical features [Car76], such as those associated with ridges, have also been explored for matching purposes [Gou94]. These differential-geometry operations have also been combined with other constraints [Ben95] and landmarks [Har99; For98b], and have been used to characterize surface structure geometry such as ridges [Aya93] and crest lines [Gue93]. An illustration of these approaches is the work of Stiehl and collaborators, who consider detection of landmarks, registration, and modeling of compound structures. In this work, a framework is created that incorporates differential operators, uncertainty, local image attributes (such as orientation of local image structure), and dynamic biomechanical brain models based upon linear elasticity theory [For98a; Fra98a]. These concepts have been extended to include other transformations, such as a technique that uses the medial axis transform in the context of multiresolutive stochastic 3D shape matching [Vem93] and deformable Fourier models [Sta92].

Matching is also being explored in the context of dynamic (or physically-based) methods [Met93; McI98]. An example is the work of Vemuri and collaborators, who have been concentrating on algorithmic efficiency for intra-modality image registration [Vem98]. In this investigation, the approach involves estimating the unknown transformation between the two images to be registered. The transformation space is represented by B-splines that can handle both local and global transformations. In the local transformation case, every point of the image undergoes a different transformation, while in the global case, all the image points undergo the same transformation. The researchers have developed a modified Newtonian scheme that involves precomputation of the Hessian of the objective function and thus does not require its computation at every iteration (unlike the case of standard iteration). This precomputation results in significant computation speedup.

Another illustration of deformable models used for matching a template of an organ is that developed by Montagnat and Delingette and described in [Mon98; Mon97; Del98]. In this approach, a reference model has been created from the Visible Human dataset [Ack98]. Using properties of simplex meshes, the reference mesh is deformed using hybrid local and global constraints. Following rigid and affine (non-rigid) registration, the hybrid deformations are introduced which can produce different levels of detail. The sequence in Figure 8 summarizes these steps to register a template of a liver to segment a patient's liver, which will subsequently be textured and used in a hepatic surgery simulation system, as described later.

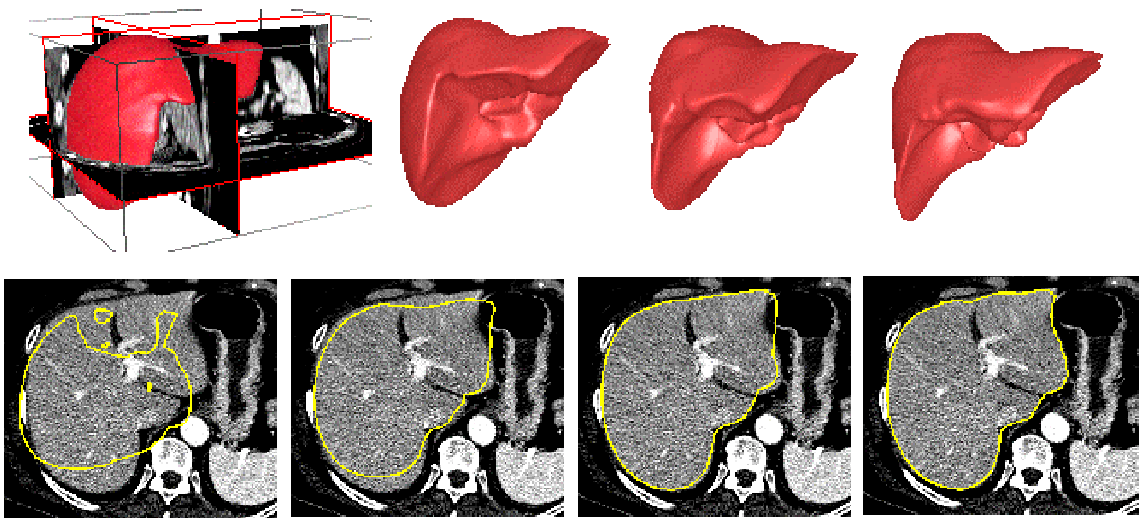


FIGURE 8 Segmentation of a liver from abdominal CT-scans. Using properties of simplex meshes, a reference mesh is deformed using local and global hybrid constraints. Courtesy of Nicholas Ayache, Hervé Delingette, Johan Montagnat and L. Soler, INRIA, France [Del98; Mon98; Mon97].

Some algorithms based on iterative point matching [Zha93] and on maximization (or optimization) of mutual information (MI) show promise in terms of robustness and independence of landmark selection [Col95; Mae97]. Optimization of MI can be viewed as a way to drive the automatic affine registration of the datasets to be matched, for example, by driving automatic thin-plate spline warping [Mey98]. Recent applications in neuroanatomical MR image registration using maximization MI methods have been reported in [Wel96; Lev98a]. In a closely related approach, the results of a registration step are evaluated at every point of the combined volume using voxel similarity measures based on intensity values [Stu96; Wel96], where a coarse match is improved by adjusting position and orientation until the mutual information between both data sets is maximized. Parameter-free elastic deformations for both 2D and 3D image registration are also described in [Pec98; Pec99], while 3D-to-2D matching [Lav91] and registration is important for image-guided applications.

Part of scene interpretation is labeling, which is useful in recognizing, classifying, and studying in greater detail specific features or components found in a complex scene. In this regard, Höhne and collaborators at the University of Hamburg have created a system that uses a KB to provide spatial and semantic descriptions of morphology, function and blood supply within the framework of a brain model or Atlas (Voxel-Man/Brain) [Höh95; Pom94; Seb93]. In this approach, the 3D model embeds knowledge derived from MRI data to create a volumetric dataset whose voxels contain descriptive information. A visual summary of the approach is given in Figure 9, which shows a visualization environment consisting of the anatomical model and other relevant information that can be interactively navigated by the user, and a diagram showing the labeling and knowledge-based interrelationships associated with the approach. The system permits exploration of the anatomy on the computer screen in a style that may be described as a digital dissection [Pfl98; Sak97]. As with other systems [Ezq99], the Voxel-Man/Brain system supports interactive visualization and queries, and offers a variety of user interactions including user-assisted segmentation [Höh92b; Sch92a].

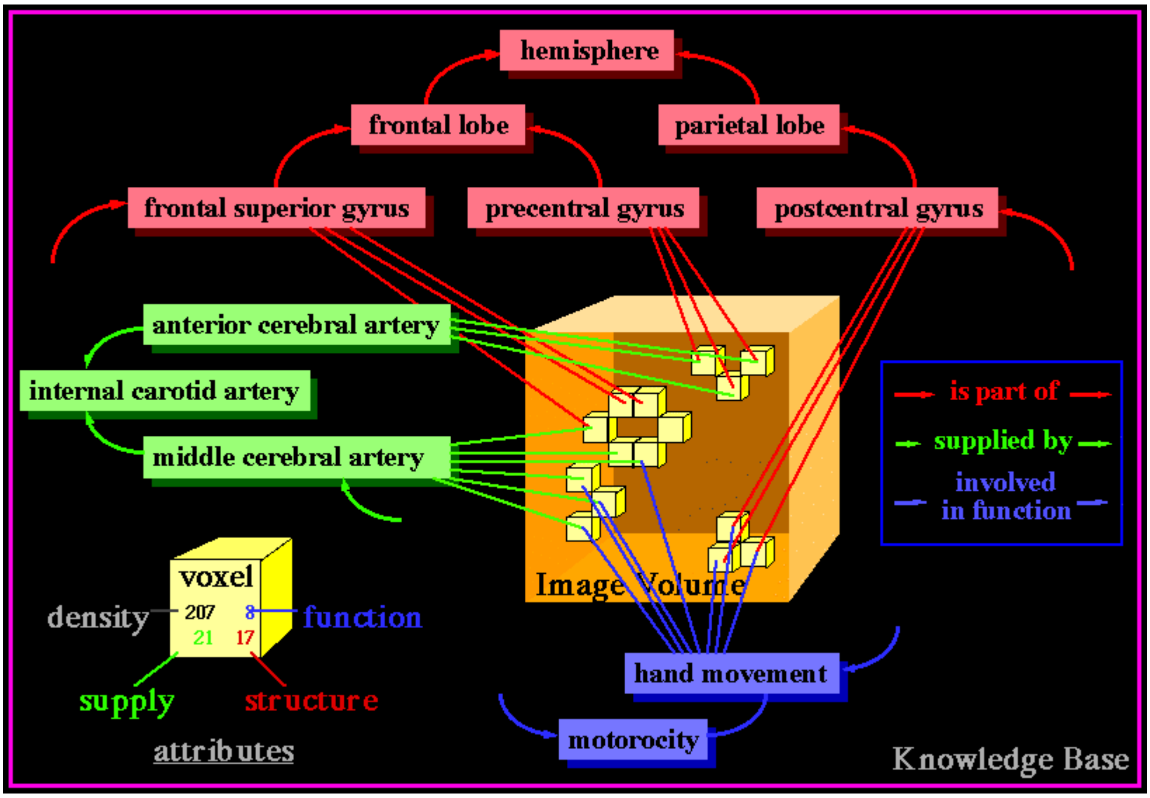


FIGURE 9A Symbolic modeling of human anatomy. Diagram of the intelligent volume model which integrates two levels of knowledge: the upper level provides a symbolic description of anatomical objects and their relations, while the lower level provides the spatial description of these structures. Courtesy of Karl Heinz Hoehne, University of Hamburg, Germany [Pom94; Sch95; Hoh95; Pfl98].

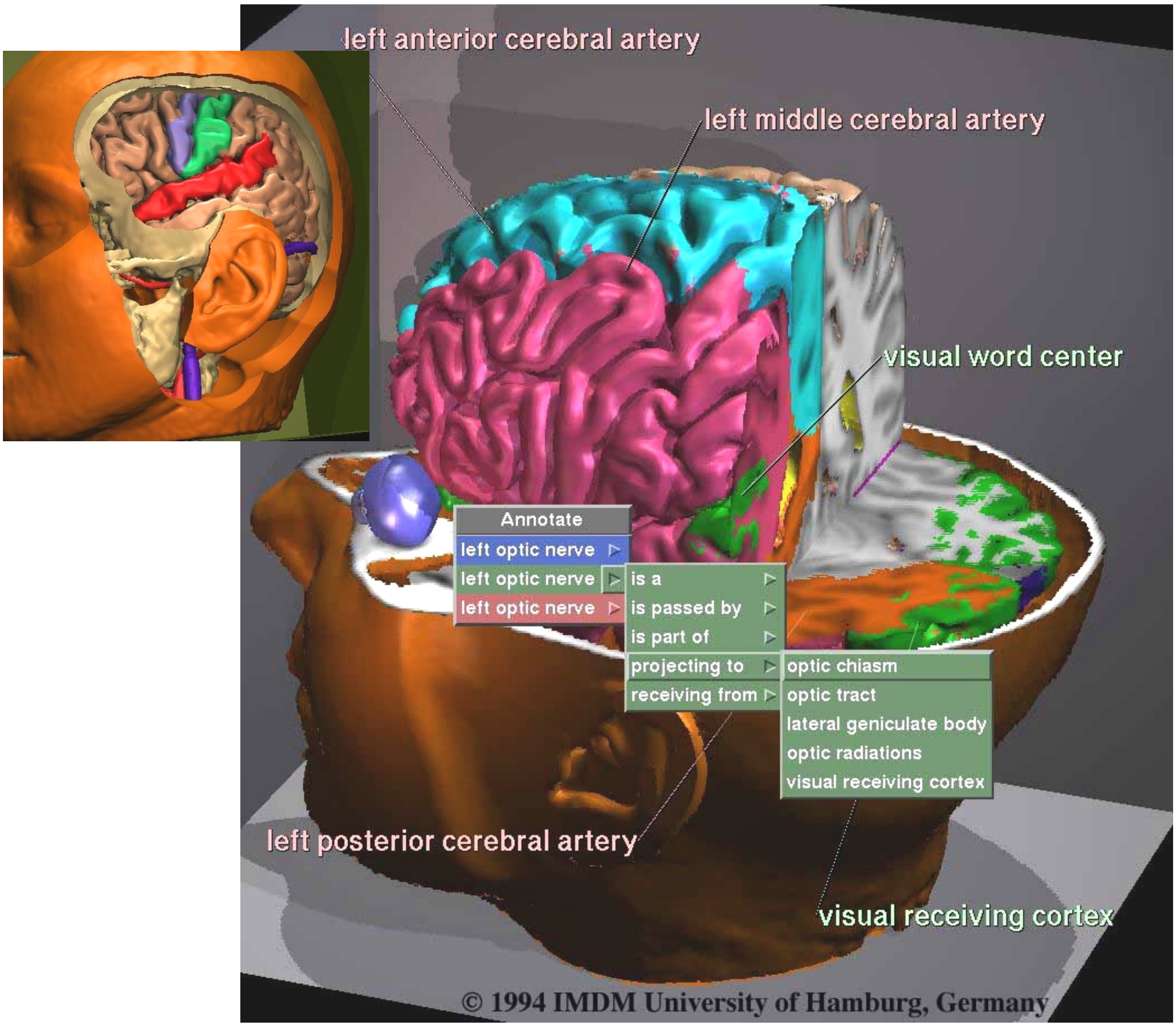


FIGURE 9B Investigation of anatomical structures in VOXEL-MAN/brain. The popup menu describes which objects are present at a user-selected point, and how they relate to other objects. Courtesy of Karl Heinz Hoehne, University of Hamburg, Germany [Pom94; Sch95; Hoh95; Pfl98].

Labeling is also important in the reconstruction of 3D models from limited views. An example is the labeling of arterial structure in 2D angiographic views, which would facilitate the 3D reconstruction of an arterial model. An example is an approach reported in [Ezq98], which resolves image ambiguities by considering different frames in a sequence and employs both model- and knowledge-based labeling methods. The process first requires enhancing [Fra98b], segmenting [Dui99; Mas98; OBr94; Sat97a; Sat98a], and tracking the vascular structure over time [Hyc92] in order to match and label the main vessels in separate frames. Matching and labeling are accomplished by using a geometric representation of the coronary arterial tree [Dod92], a semantic model, and dynamic programming methods. The labeling process is iterative, converging to a global labeling hypothesis for the entire tree (rather than a labeling hypothesis for only parts of the tree). As reported in [Ezq98], the results obtained from testing the system with numerous clinical images demonstrate the viability of using a fusion of model- and knowledge-based methods. An illustration of the type of labeling that results from using this comprehensive procedure is shown in Figure 10.

Labeling of bronchial branches using model-based methods are also described in [Mor98]. Connectionist methods have been used with relative success to segment images [Che91], to interpret 3D cardiovascular SPECT imagery [Ezq92], and to predict myocardial function [deB96a]. KB systems have been applied to image interpretation, as reported in [Dha90a; Dha90b; Mal96; Alc96].

A fundamentally different approach to interpreting images uses "mining" operations applied to medical image DBs. In recent work reported in [Coo99], innovative mining methods are explored to uncover possibly interesting or medically meaning association from medical information. The concept of mining is well known in business applications, where there is an interest in examining thousands (sometimes millions) of records to uncover associations, such as whether sales of item X accompanied sales of item Y, for instance. With this in mind, "mining" or "knowledge discovery" algorithms have been proposed to uncover such patterns [Agr93; Ull88]. As reported in [Coo9], the goal is to modify these mining algorithms such that they can be applied to cardiovascular image and non-image data, with the overall objective of uncovering potentially useful patterns that might provide evidence of coronary artery disease. A schematic depiction of the overall process is shown in Figure 11. The preliminary results, as reported in [Coo99], show that carefully constructed mining algorithms coupled with medical imagery and other DBs can discover patterns and associations relating disease to clinical findings. A related concept is that of retrieving images, which may also prove useful for indexing into large image DBs [Dec95].

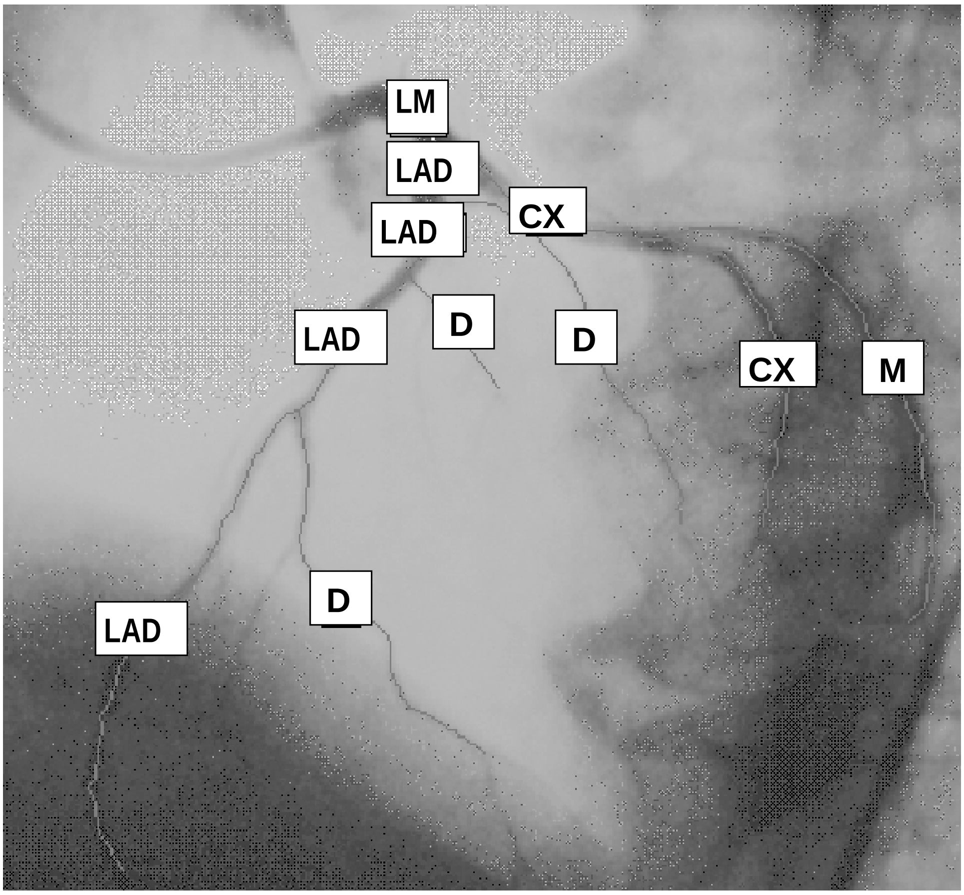


FIGURE 10 Labeling of arteries resulting from a unified model- and knowledge-based approach [Ezq98].

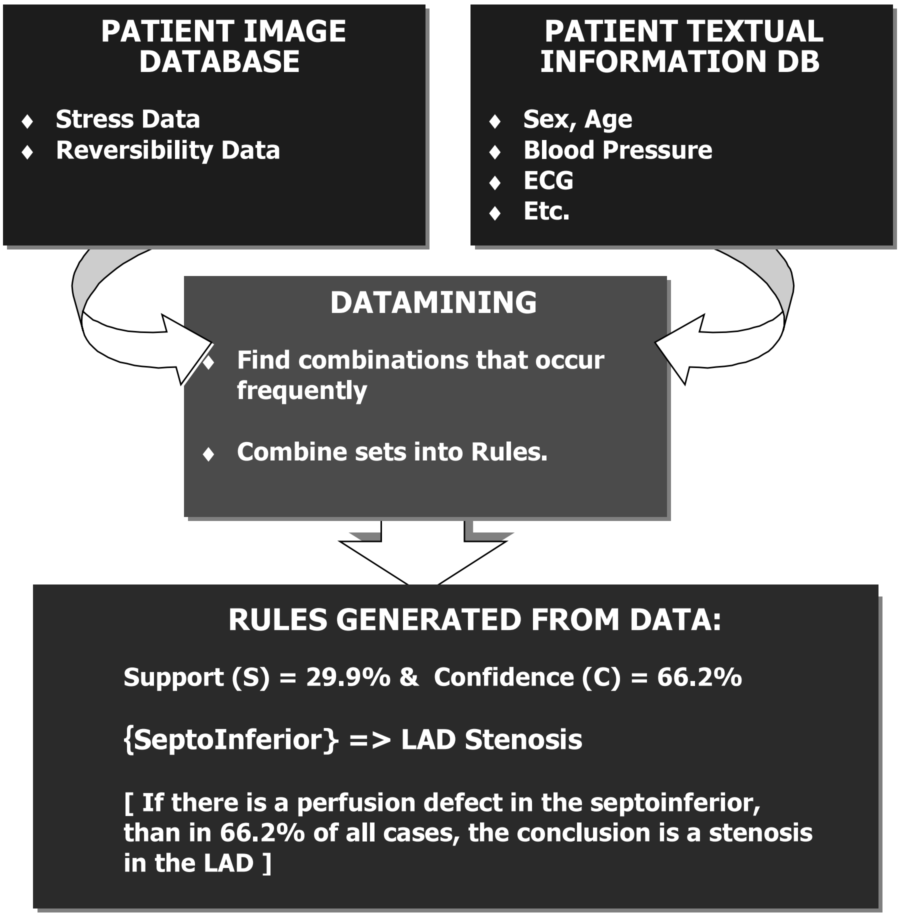


FIGURE 11 Overview of knowledge discovery resulting from mining medical image databases [Coo99].

4. SYNTHESIS

The overall objective of this stage is to synthesize an image or mode, creating representations of the structures or processes of interest, and subsequently displaying these models in an appropriate manner that can convey the structural and dynamic characteristics, while also supporting various types of user interaction. In terms of the foundational principles, readers are referred to a wealth of literature devoted to describing the methods of 3D graphics and animation [Fol90; Wat93], interactive visualization [Nei97; Man94; Bro92], display hardware considerations [Sof98], and numerous surveys, reviews and tutorials in the context of medical imaging applications that have been published recently [Sha98; Gro98; Rho97] and over the last few years [Bar93; Udu91; Sty91; Höh90a]. In medical imaging, both surface- and volume-based methods are currently being applied to visualize medical imagery.

One of the first methods used to represent and visualize surfaces from medical volume data was the Cuberille model [Che85], where a grey level volume is first binarized, and a list of square voxel faces is subsequently created to denote the borders between voxels lying inside and outside the object enclosed by the surface. A surface extraction method was introduced in a seminal paper by Lorensen and Cline [Lor87] in which they described the Marching Cubes (MC) algorithm. Numerous versions of the MC algorithm have been developed [Nin93; Wil90; Wal91], including ways reduce the number of polygons without appreciable loss in information or detail [Sch92b]. At present, one of the most common approaches to achieve surface-based rendering is to use the MC algorithm in conjunction with either normal vectors of the polygons or grey-level gradients computed from the volume data [Pom90; Tie90; Höhne86]. Surface detail is also widely used, especially in augmented reality applications where a 2D image (for example, an ultrasound image) is combined with a 3D data model, such that the US image plane aligns with the orientation of the plane in the 3D data [Sof98].

Another type of representation is through active surfaces [Sin98] and active volumes [Bro95; Coh93], thereby providing a framework for describing both shape as well as behavioral characteristics of object surfaces and object interior [Cot96]. Dynamic modeling can be further combined with different geometrical representations such as finite-element (FE) modeling (FEM) . An example of these methods is the facial surgery planning and surgery training work of Gross and collaborators. Part of this work, described in [Koc96], is concerned with creating a model of the human face from CT volume data using prism-shaped elements, and synthesizing soft-tissue deformations with a physically-based (PB) approach within an FEM framework [Rot98; Koc98; Koc99]. In a related project by the same group, the goal is to develop a soft-tissue surgery trainer system as explained in [Bie98], where the emphasis is placed on both the formulation of efficient representations of the underlying anatomical structures with deformation properties, and also on the efficient computations to provide real-time dynamic deformations and feedback. The geometrical representation is achieved using common tetrahedralization methods to create models, combined with texture mapping to enhance the visual realism. The collisions between the tetrahedra and the virtual scalpel are calculated using a local collision-detection algorithm, and the underlying dynamics are expressed using a system of masses and springs attached to each tetrahedral vertex and edge, respectively. Relaxation is performed using hierarchical Runge-Kutta iteration by traversing the data structures in a breadth-first order. The method is partially illustrated in Figure 12. Current investigations center on improving computational efficiency, especially during cutting procedures.

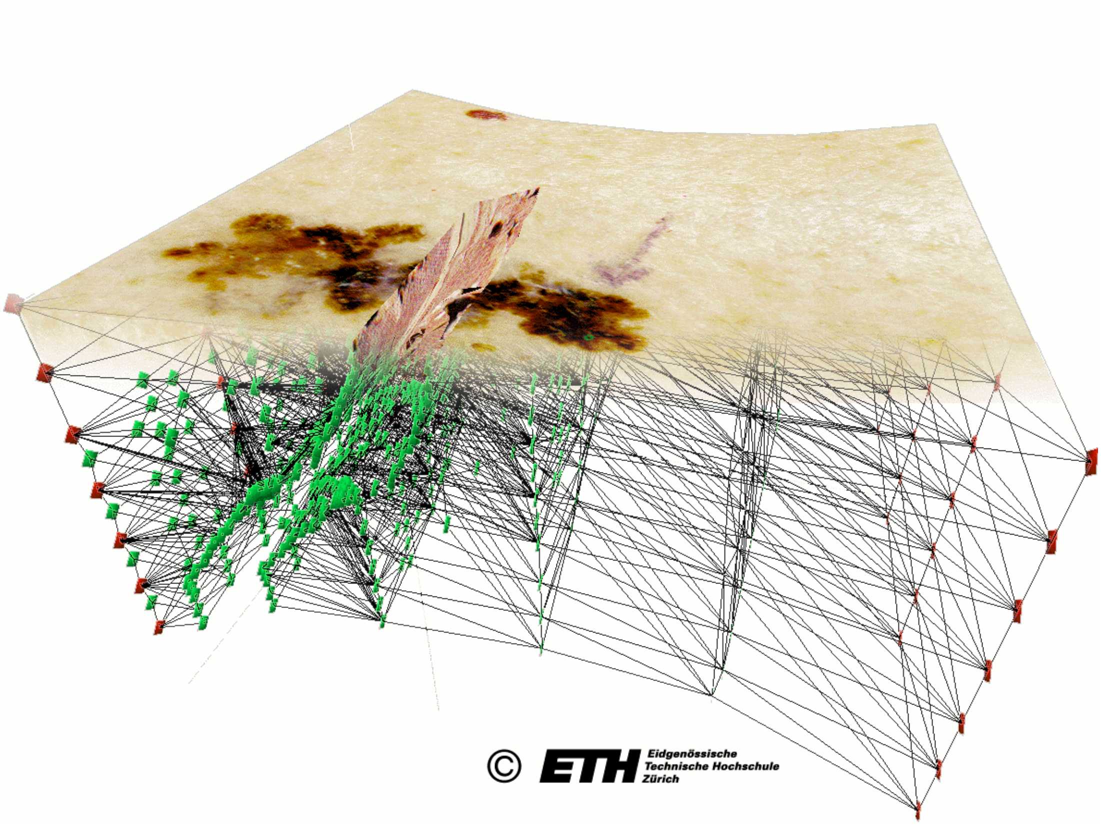


FIGURE 12 The image illustrates the internal tetrahedral mass-spring structure of the virtual tissue used by the ARTiST surgery simulation prototype. The edges connecting the masses are modeled as springs representing the elasticity of tissue. As can be seen near the cut, the tetrahedral mesh in the neighborhood is adaptively refined as new tetrahedra get introduced during the cut. Courtesy of D. Bielser, M. H. Gross, Computer Graphics Group, Swiss Federal Institute of Technology (ETH), Zürich, ETH. [Bie 98; Rot98; Koc98].

Spring-based models have also been used in applications such as gall bladder surgery simulation, where the goal is to create shaded (or texture-mapped) representations of internal organs that facilitate interactive deformations [Cov93], as illustrated in Figure 13. Superquadrics have also been used within a PB framework to model elastic behavior, such as the facial modeling work described in [Ess93], and in the work of [Bro95]. It is also possible to combine some of these approaches, as well as to introduce additional transformations of the data. For instance, dynamic and topology-independent shape modeling using geometric curve/surface evolution is explored in [Mal95], while surface reconstruction using a wavelet-basis is reported in [Lai97].

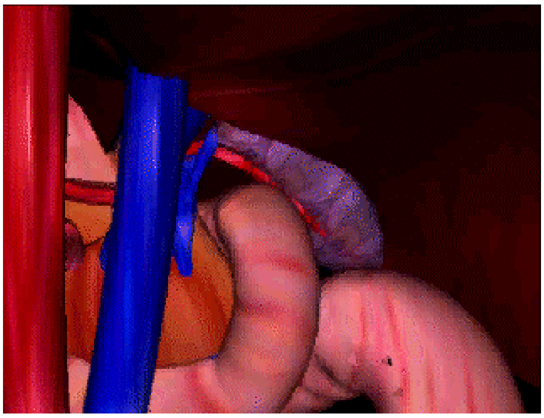


FIGURE 13 Scene of internal organs with texture mapping for surgery simulations [Cov93].

Direct volume rendering methods are also widely used in medical imaging to display fine structure, and to highlight the contrast between hard and soft tissue [Sha98]. A common approach is to utilize ray-casting and the "additive projection" concept, in which the image consisted of an average of the voxel intensities along the parallel rays [Har78; Höh87], resembling X-ray image traversal. An illustration is the work of Groeller and collaborators [Cse99a; Mro99]. In one line of investigation, research conducted by this group centers on the optimization and quality improvement of the maximum-intensity project (MIP) algorithm. The work is motivated by the fact that occlusion can frequently hinder the visualization of volume information, which requires that the dataset be rotated to facilitate viewing from different directions. To improve computational speed, this group has developed an algorithm that generates MIP images using parallel projection and templates, such that voxels that are expected not to contribute to a projection based on neighborhood considerations are removed during preprocessing. The remaining voxels are then stored in a manner that optimizes cache coherency independent of the viewing direction. As a result, the method permits accelerated rendering of large volumetric datasets. Figure 14 typifies the type of visualization results that are possible with this method.

FIGURE 14 Maximum Intensity Projections (MIPs) are used to illustrate vascular structures [Cse99a; Mro99].

Published by the Eurographics Association ISSN 1017-4656

In addition to using different types of viewing modes, frequency-domain characteristics can also be used to visualize 3D data [Tot93], although these transformation-based methods are not as common as the surface- and volume-based rendering techniques. Newer algorithms have been proposed to speed up volume rendering calculations [Avi92; Cub4ONL]. Another important aspect of the visualization of data is the degree to which the information is faithfully represented and displayed. The problem associated with the evaluation of visualization algorithms is two-fold: first, there are no widely accepted quantitative standards with which to measure either image fidelity or accuracy, and second, it is also difficult to measure usability (i.e., the degree to which a particular visual rendition is useful). An approach to assess image fidelity is through the use of simulated data [Mag91; Pom90; Tie90] as well as data acquired from corpses [Dre89; Hem85; Ney91b; Pom91; Rus9; Ack98]. Other ongoing activities to assess image fidelity continue [Höh92a; Tie98; Cut91].

5. INTERACTION

Over the past several years, a number of technologies have been introduced with which to see, touch, hear, or generally perceive objects or situations in order to meet certain task-oriented goals. It is important to recognize that there are distinct types of perceptual channels and thus different levels of perceived realism: visual, behavioral, interaction, and collaborative realism. In visual realism, the goal is to create scenes that "look" real, i.e., combining imagery, perceived motion, and other visual cues that together result in a degree of realism that is sufficient for a particular application. Behavioral realism refers to the degree to which the system seems to "behave" as might be expected under specific situations, including interactions between physical forces such as gravity or collisions). Interaction realism represents the "feel" of the system: i.e., how behaves or responds when the user interacts with it. Collaborative realism refers to the degree to which remote communications, such as point-to-point or multi-point connections between geographically dispersed, appears real.

To support the creation of these types of realism, novel interaction devices and environments have emerged in areas commonly known as virtual reality (VR) or virtual environments [Bar95; Kal93; Hof97], and augmented reality (AR) [Azu97]. The overall goal of these systems is to establish a sense of "presence" from the user's perspective. A closely related notion is the concept of an avatar, which can be viewed as an agent or a symbolic figure that inhabits, and interacts within, these virtual environments (akin to the way an iconic figure that represents a human player in a video game constitutes that player's avatar). In the medical imaging context, a virtual model used for surgery rehearsal might be considered to be an avatar of the real patient leading to the notion of a patient avatar [Sat99], which can be viewed as a complete representation of a person's anatomy.

There is a significant number and variety of tools and devices, including those that exploit human binocular capabilities (e.g., head-mounted displays (HMDs), boom displays) , force feedback (FFB) or haptics devices, and subsystems for tracking and providing a sense of orientation (propioceptive) [Bau96; Che98; Aya97; Aya98; Che98; Cot99a; Cot99b]. Other systems simultaneously combine several input and output subsystems to create immersible environments where the sense of presence is heightened such as the Cave and Workbench systems [Kru94]. The algorithms, hardware and software systems, robotic subsystems, peripherals, tools, and techniques underlying these concepts span several areas and years of work, and have been used in a number of medical applications, as summarized in [Sof98; Sha98; Daw98; Gro98; Kra98].

Since user interaction can involve such complex tools and techniques, the concept of a user interface takes on a broader -and more important- meaning. It thus becomes vital to invoke human-computer interaction (HCI) principle and methods for properly designing a user interface (or interaction mechanism) [Sch87; Ras86; Loh94; Kle89;]. Cental to this is the idea of reduction of workload: cognitive, perceptual (especially visual), and/or motor workload. Thus, the design process would require that user workload be carefully examined, defined and facilitated through a proper UI. This design process consists of creating UI prototypes that can be iteratively refined, re-evaluated and re-designed. This iterative sequence of design-evaluate-redesign essentially form the core of usability studies. An example of an interactively designed UI is shown in Figure 15, which shows the screen used to reconstruct 3D models of coronary arteries to facilitate the assessment of, and treatment planning associated with, coronary artery disease [Dui99; Fab99]. As shown, several views corresponding to intermediate steps in the reconstruction process are provided to the user, allowing him/her to intervene as appropriate. The system for vessel reconstruction is currently being implemented in a number of centers for clinical evaluation and usage [Fab99].

Published by the Eurographics Association ISSN 1017-4656

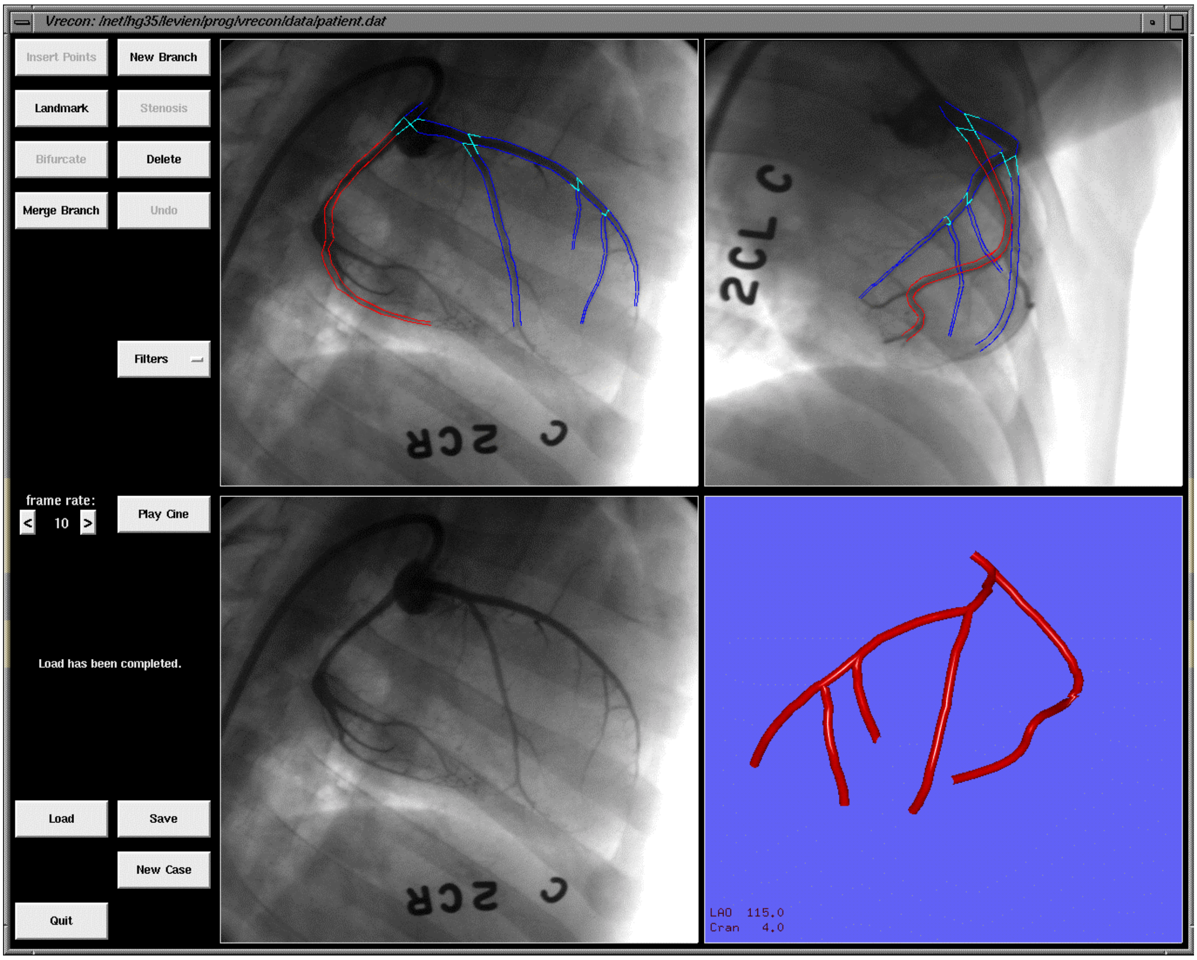


FIGURE 15 Interface Supporting the 3D reconstruction of coronary vasculature [Dui99; Fab99].

HCI principles and methods mentioned above become increasingly important as the interaction becomes more complex, as in the case of multimodal or multisensory interactions. At present, well established methods for evaluating VR and AR systems are still largely in nascent stages [Ell96; Che98; Sat96; Sat98b]. Another issue is computational complexity. As an illustration of the computational costs that might be involved in simulations, a highly detailed model of a human heart used to simulate different configurations of electrodes, their sizes, and the magnitudes of defibrillation [Joh97ONL], is based on finite-element methods requiring 1.5 million tetrahedral elements, 250,000 degrees of freedom and 4 billion floating-point operations: a computational problem that was solved in semi-interactive time using a 14-processor computer [Sof98]. Hence, fast processing is essential in medical VR and AR applications, requiring the management of numerous resources (some of which may involve heterogeneous platforms), controlling several I/O (input/output) operations, and performing fast calculations. One possible benchmark for medical applications is real-time output of at least 10-15 frames per second [Sof98; Wie96]. From a perceptual viewpoint, the ideal goal is "real-time" response with unnoticeable latency and lags in all perceptual channels. In this regard, the delay between user input and system response must be less than 100 milliseconds and ideally less than 10 ms. The update of a haptic feedback device is particularly demanding, estimated to be in the range of 100 updates per second [Che98; Sof98].

6. APPLICATIONS AND TRENDS

6.1 VISUALIZATION OF MEDICAL DATA

It would seem that diagnostic visualization of 3D medical data would be one of the most direct and natural applications of the methods discussed thus far. However, as has been pointed out before [Sha98; Rho97; Sak97], this is actually not the

Published by the Eurographics Association ISSN 1017-4656

case. There are a number of compelling reasons for this counterintuitive circumstance. One reason is that radiologists (and other clinical specialists) have traditionally been taught to interpret or "read" 2D images rather than 3D volumes (or 3D models). Another consideration is the discrepancy, sometimes considerable, that has been noted between the information that is presented volumetrically and that which is shown in 2D formats [Sha98; Kle89; Mar93; Rog90]. Additional difficulties arise due to the lack of 3D visualization standards, and the absence of reliable and consistently accurate segmentation algorithms [Rho97; Sha98; Aya95a]. As a result of these considerations, clinicians seem to generally prefer (and perhaps primarily trust) 2D images over 3D volume representations.

Despite the challenges mentioned above, a number of clinically successful applications to specific 3D data visualization problems have been reported over the past several years [Pfl98; Sak96; Str97; Aya95b; Bon96; Zon94], including anthropological applications [Kal92]. In general, it appears that for applications to be clinically useful and attractive, more than "passive" displays or "simple" 3D viewing is generally required: some value-added functionality, complementary information or clear clinical advantage in the presentation of the data should be introduced [Sak97; Rho97]. To address some of these challenges, a number of research groups are exploring novel visualization techniques as discussed next.

Atlases and The Visible Human

Perhaps one of the most notable recent achievements in visualization of 3D medical data is The Visible Human Project, an initiative organized and financed by The National Library of Medicine of The National Institutes of Health in Baltimore, Maryland, USA, and spearheaded by Ackerman, Spitzer and Whitlock [Ack98; Spi92]. This dataset is made up of scans of two human bodies (one male and one female) using three modalities (CT, MR and photomammography), thereby providing a full set of 3D information [Tie96]. The dataset is large, consisting of nearly 14 Giga Bytes, which after segmentation and polygonalization with two polygons per voxel results in approximately 9 billion polygons [Lor93ONL] (for clarity, giga and billion correspond, respectively, to 106 and 109 quantities). In many ways, the creation of this dataset represents a landmark event. First of all, the project can be viewed as a model for successfully acquiring high-resolution, high-fidelity data on the entire body. In addition, the project was designed (and fulfilled its commitment) to make the data widely available. Moreover, the project provided a model for the successful, high-demand, high-volume transmission of data to researchers throughout the world. Furthermore, it was also a convincing demonstration of the power of the Internet as an effective medium to disseminate research data. And, in a certain sense, the project created what may be regarded as the "benchmark" dataset with which to compare different research results.

In addition to the Visible Human data, a number of research groups have built reference 3D data models called **Atlases**. The general objective of these efforts is to be able to provide structural and relational descriptions of organs for a number of applications: education, comparisons with a particular patient's dataset to the reference Atlas (e.g., to label anatomy and assess the extent and severity of pathology), and/or for pre-operative planning and rehearsal. In the case of making comparisons between actual data and a reference Atlas, the Atlas is warped using both rigid and non-rigid deformations to match anatomical landmarks, features, or other target points in the patient's data. The process gradually integrates more of the information that relates different features between the two datasets. The idea of building brain Atlases has been explored for some time by Höhne and collaborators [Höh92c], including labeled Atlases [Plf98], as shown in Figure 9, and also by researchers at the Montreal Neurological Institute, who investigate the creation of models that use a priori information within a probabilistic framework [LeG98]. In addition, finite-element methods [Kyr98], biomechanical kinematic models [Mur98], diffusion-tensor methods [Pou98a], and other deformation-matching approaches [McI98; Mil93; San95; Sub96] have been used in Atlas construction and manipulation. Automated Atlas integration for functional neurosurgery has also recently been reported [StJ98]. The construction of reliable Atlases may well represent the pioneering efforts on the way to creating whole-patient avatars [Sat99]. The development of such generalized Atlases, coupled with information such as that derived from The Visible Human Project, will be a pivotal step toward making "universal" datasets more widely available.

Interactive Visualization of Multidimensional Data

One line of investigation centers on the presentation of information in formats that particularly benefit a specific application and/or which emerge from usability testing and UI redesign. For instance, Groeller and collaborators are examining the concept of "magic mirrors" to create multiple views of fMRI volumetric data of the brain [Koe99; Cse99b]. In this effort, transfer functions are used within the framework of direct volume rendering with the objective of separating different regions of the data by specifying distinct color and opacity values in the transfer functions. Although all of this information can be contained in one visualization model, it is sometimes difficult for the experience viewer to visually comprehend all of the information in an intuitive manner. Hence, the combination rendering based on transfer functions, combined with magic-mirror projections and texturing effects, can produce enhanced visualizations that may help to more clearly distinguish various structures of interest. An illustration of this work is displayed in Figure 16, which shows a 3D model of brain data that can simultaneously be visualized in different presentation formats.

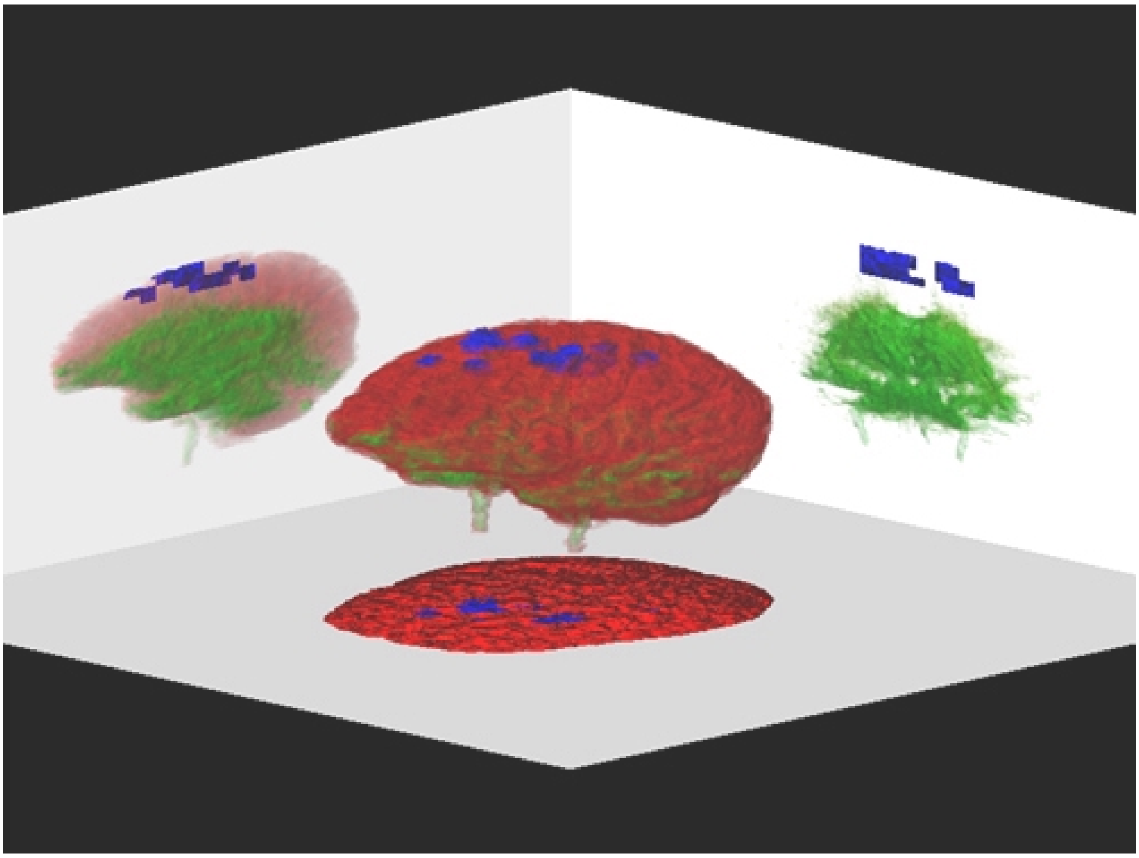


FIGURE 16 3D contour map of the brain and activated regions mapped onto the Magic Mirror at the left hand side of the scene. The usage of other techniques like maximum intensity projections, orthonormal cuts, color encoded cuts, or segmentation maps as Magic Mirrors is also possible. Courtesy of Eduard Groeller, Vienna University of Technology [Koe99; Cse99b].

A similar presentation philosophy is used by Ezquerra, Garcia and collaborators to display 3D cardiac information, as described in [Fab99; Pei92]. The approach is illustrated in Figure 17, which shows a panoramic view of myocardial perfusion distribution obtained from SPECT imagery. The rationale for this type presentation stems from several challenges, including the need to assess the distribution of perfusion (blood flow) throughout the entire myocardial mass as well as the need to be able to assess the location, extent and severity of possibly hypoperfused regions that my be related to each other [DeP89; [Ezq99]. Another reason is that most experts who can clinically interpret these images have traditionally been trained to visualize the perfusion information in 2D display formats [Coo90]. Thus, a single 3D model may not be the most useful representation. Consequently, clinicians can directly benefit from viewing both local as well as global perfusion distribution characteristics. Based upon these considerations, and after extensive usability testing, an interface design has evolved that can provide regional quantization, myocardial volume orientation [Mul95], and global perfusion distribution information in a presentation format such as that shown in Figure 17 [Fab99; Fab95; Pei92].

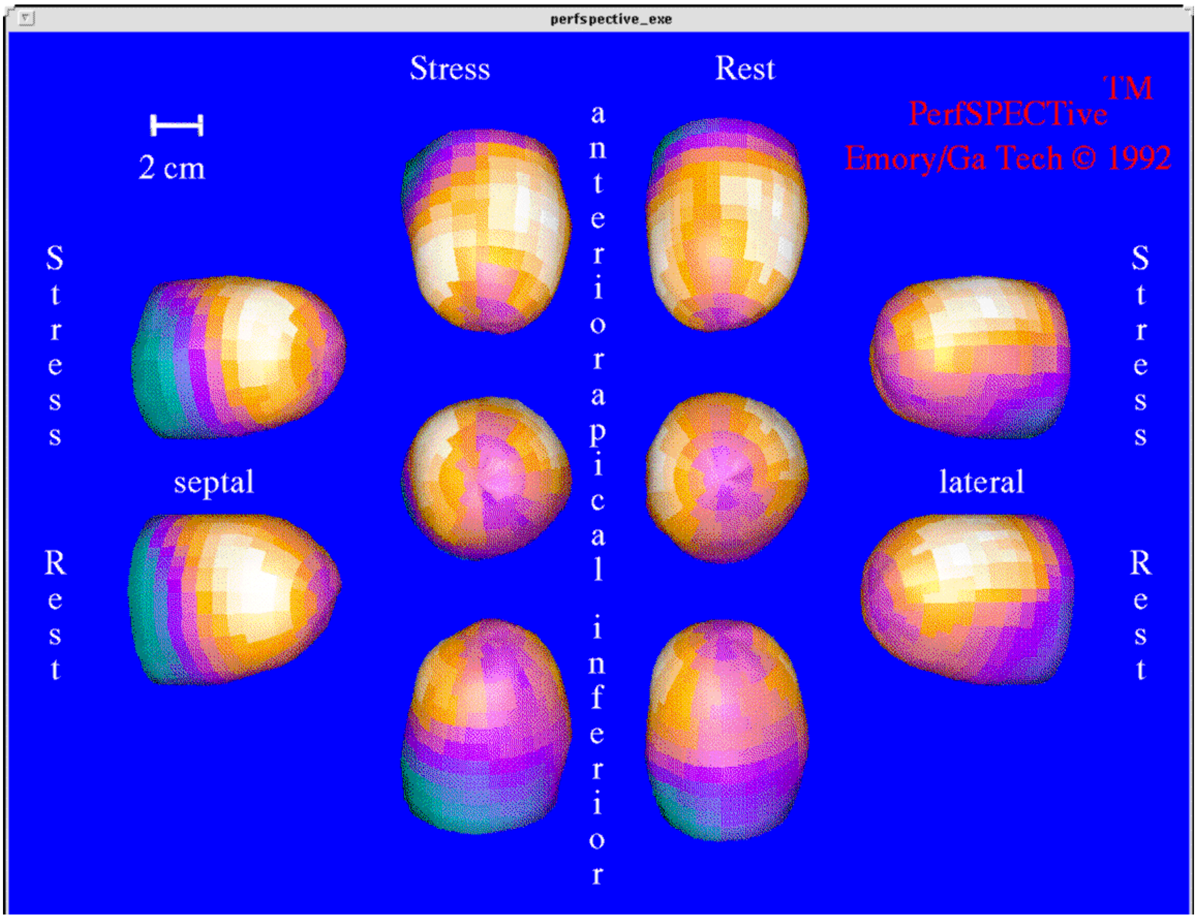


FIGURE 17 A multimodal presentation of a 3D myocardial distribution model[Fab99; Pei92].

In the work conducted by H.P. Meinzer and collaborators, the general emphasis is placed on investigating and developing approaches to visualization problems directly within the clinical environment [Dem97]. In one project carried out by this group, Glombitza and colleagues are developing a method for conducting volumetric evaluations of intracardiac blood flow based on dynamic 3D echocardiography [Glo99a; DeS99]. The overall objective is to quantifiably assess heart valve defects, such as mitral regurgitation. The method employs thresholding to discriminate between fast turbulent flow and slow displacement flow, where the former can be used to describe regurgitant jet flowing into the atrium while the latter is caused by blood that has been in the atrium before regurgitation. Volume evaluation is carried out automatically, producing an objective assessment of mitral regurgitation that has been shown to be more exact than conventional 2D methods [Glo99a]. This volume visualization method thus represents a "3D color Doppler" technique that extends the color-coded quantification normally used in 2D displays.

Matching, Registration and Multimodality Fusion

The idea of integrating the information derived from different imaging modalities, comparing images of the same modality (and of the same patient but taken at different times), or contrasting patient-specific data to models or Atlases, collectively represent one of the earliest and most common applications of interactive visualization methods [Els93; Bes92; Met93; McI98]. Certainly one of the main areas of application is neuroanatomy. Given the difficulties associated with the complex surface structure of brain matter, coupled with the medical importance of this application, brain image registration and fusion have continued to receive a great deal of attention over the years. Atlas-based matching began to be explored in the early 1980s [Baj83], and more recently non-rigid matching of tomographic images based on a biomechanical model has been reported

Published by the Eurographics Association ISSN 1017-4656

[Hag99]. An illustration of neuroanatomical applications is the work of Stiehl and collaborators, who consider detection of landmarks, registration, and modeling of compound structures [For98a; For98b; Fra98a]. Another example is the work of Vemuri and collaborators, who consider intra-modality image registration using B-splines and precomputation steps that result in significant execution speedup based on tests with numerous MR data sets [Vem98].

Another clinically important area is that centered on cardiovascular applications. In this area, model-based matching approaches have been applied to track left-ventricular (LV) wall motion [Ami98; Cla97]; 3D curvature features of the LV [Fri92] and cerebral blood vessel exploration system [Pui97a; Pui97b]. Similarly, non-rigid wall motion dynamics have been studied using modes and fast-Fourier transformation (FFT) features [Nas94b; Sta92]. In ultrasound, vascular structure has been integrated with anatomy [Mis91], such as the fusion of intracardiac blood flow [DeS99; Glo99a]. An illustration of a current cardiovascular application is that described in [Fab99], where 3D models of both arterial structure and myocardial function are fused together to create a combined anatomical-physiological model that interrelates structural and functional information. The arterial model is created from ciné angiography [Ezq98; OBr94] and superimposed on a myocardial perfusion distribution model obtained from gated SPECT imagery [Pei92]. Natural landmarks, such as the intraventricular grooves associated which the location of major vessels, and an iterative closest point algorithm, are used to fuse the two models. Such a unified model, exemplified in Figure 18, is created for each patient automatically and quickly; the approach is undergoing extensive clinical evaluation [Fab99].

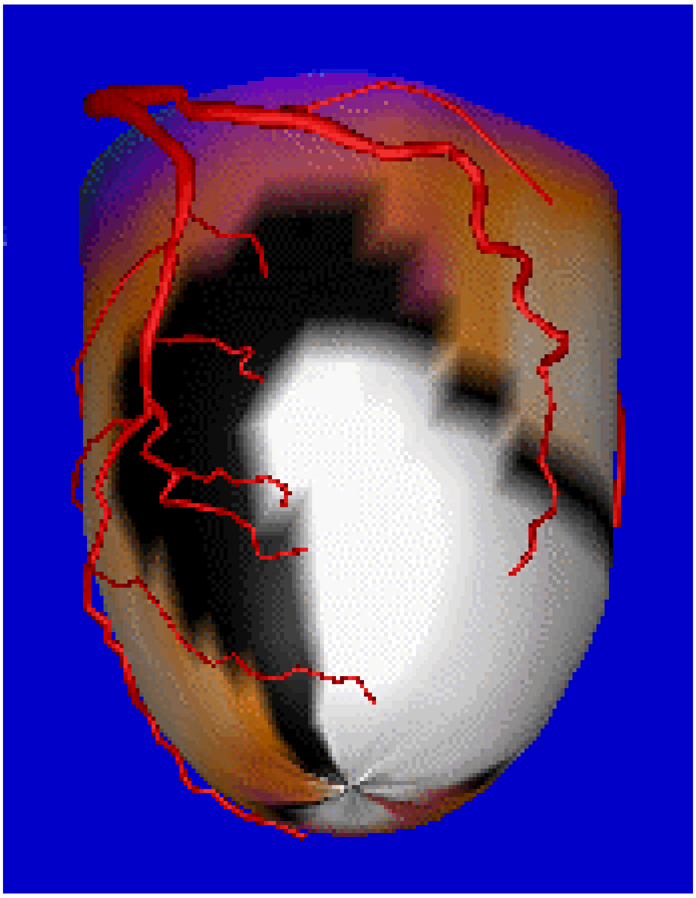


FIGURE 18 Fusion of patient specific 3D coronary arterial and 3D myocardial perfusion distribution models [Fab99].

Other applications consider registration or fusion of different types of data [Zah95], especially in the area of AR-based applications where images from a video camera are combined with images from ultrasound video [Sof98]. In one approach, the video camera is displayed in the background while the US video is texture mapped and displayed onto polygons appearing in a synthetic opening in the scanned patient data such that the polygon orientation corresponds to that of the US slice. The displayed polygon is then made to gradually fade after the probe moves from the corresponding position. The same group has recently developed an AR-based needle biopsy of breast lesions

[Sta96]. This application calls for the precise registration between actual data and computer-generated imagery. Registration of 3D onto 2D images has also been explored for image-guided surgery [Lav96], to combine stereo with volumetric images [Bet95], to achieve registration using skeletal near projective invariance methods [Liu98], and other applications [Ban98b]. An interesting and fundamentally different application is concerned with structure matching in proteins, as reported in [Pen94].

Knowledge-Guided Visualization

One particularly promising type of visualization approach uses KBs (knowledge bases) to interpret 3D structures or processes, or to label anatomy in 3D datasets. An example of this is the system developed and undergoing multi-center validation designed to interpret 3D cardiovascular SPECT perfusion imagery as well as other (non-image) patient data to assess the extent and severity of coronary artery disease [Ezq99]. The resulting system, called PERFEX (for perfusion expert), integrates perfusion imagery with different types of relevant patient-specific information (such as patient age, sex, symptoms, clinical history, EKG results, pre-test likelihood of disease, etc. [Dia79]) to formulate a comprehensive diagnostic interpretation using a knowledge-based framework. This KB system utilizes various models of reasoning (including uncertainty, probabilistic, temporal, and spatial reasoning models), domain knowledge derived from numerous expert nuclear cardiologists which been acquired and refined during a span of over a decade [Ezq86; Mus90]. The results of KB processing are presented to the users through an interface that has been iteratively designed to support interactive visualization and user-initiated queries (for instance, to provide the user with justifications regarding the conclusions reached by the system) [deB96b]. Importantly, the system infers structure from function: using functional information (myocardial perfusion distribution) as input, conclusions are drawn regarding which coronary vessel(s) may be diseased and the corresponding likelihood of disease (i.e., the output consists of inferences regarding vascular structure and the evidence for coronary lesions). The method has been extensively validated [Gar99; Gar96; deB96b] and is used clinically as part of a comprehensive software system [Fab99]. The system is illustrated in Figure 19.

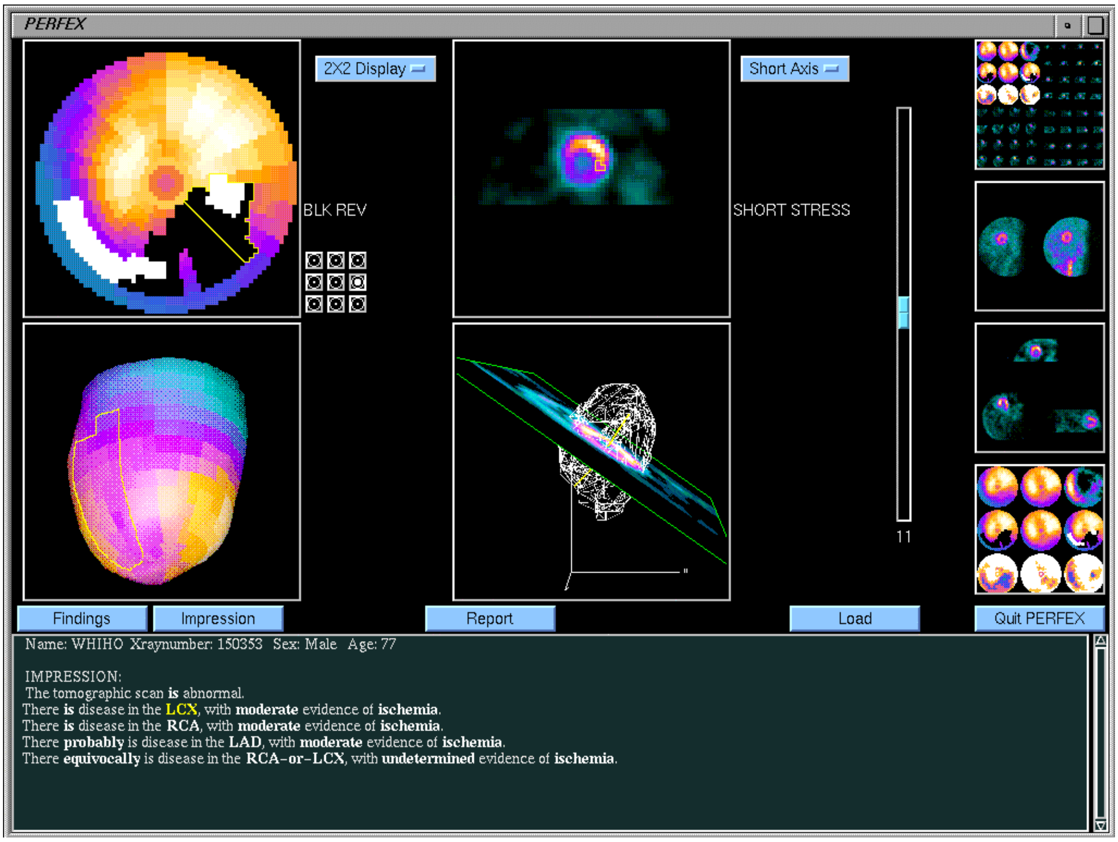


FIGURE 19 Interface design for knowledge-based 3D images interpretation and visualization [Ezq99].

General Tools and Software Systems

As the foregoing discussions suggest, several practical contributions have been made in the form of DBs, tools and software systems that support various medical imaging applications, such as the Visible Human data [Ack98; Spi92] Voxel-Man [Pfl98; Mas98; Höh95], 3DVIEWNIX [Udu94b], ANALYZE [Rob96; Rob89; Rob91], the Cardiac ToolBox [Fab99], InViVo [Sak98], and others [Nie97; LTPN96]. In terms of display hardware, a potentially important development may be computational holography including "holovideo" systems, which may be available (and somewhat affordable) in the next few years [Luc97; Chi95]. Collectively, these (and other) efforts may be viewed as representing the current generation of results from which future innovations can spring. The discussions that follow introduce current approaches to effect interaction with the data using relatively more complex interaction mechanisms.

6.2 VIRTUAL MODELS AND NAVIGATION

A potentially powerful paradigm is the creation of models designed for virtual manipulation and exploration. Although there is no exact definition of a virtual model (if we are not too restrictive, even Roentgen's original radiographs represent such a model), the term is generally used to imply that some representation of patient information is created (e.g., typically through an underlying 3D geometric or physical model, or more generally by constructing a patient avatar), with the objective of allowing the user to navigate, manipulate, deform or otherwise explore the information space (frequently through VR- or AR-based interaction mechanisms).

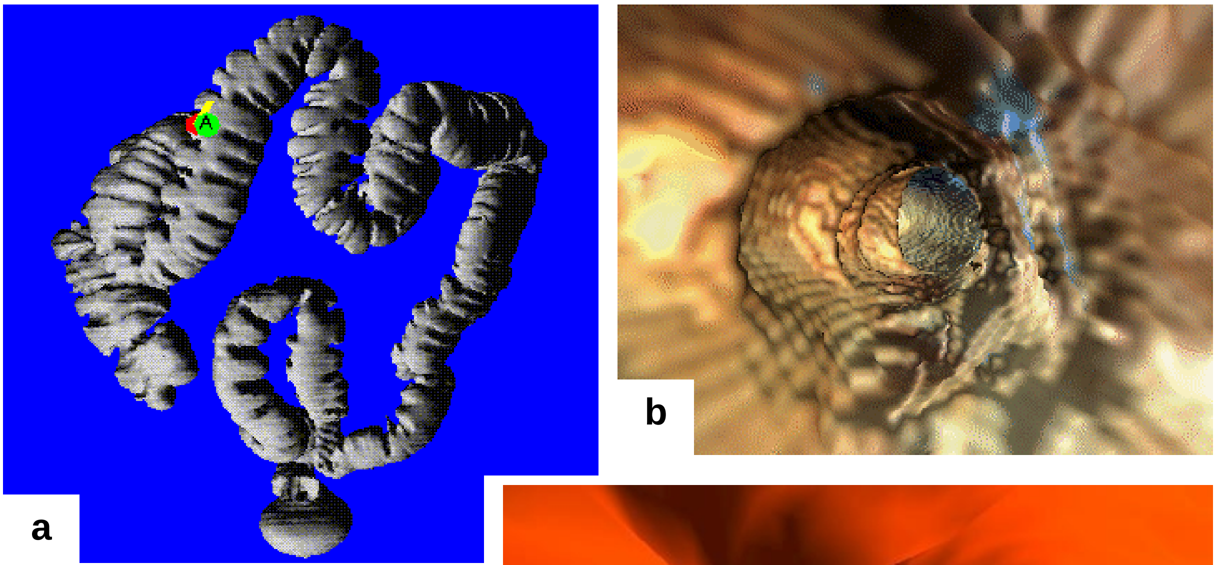
Diagnostics: Virtual Fly-Throughs

A very promising diagnostic approach is the virtual "fly-through" in which a user can explore patient-specific data. The basic idea is to acquire the patient data (using CT, MR and/or US imaging) in order to construct a representation of the patient's anatomy that is sufficiently faithful, reliable, and accurate, and which exhibits sufficient level of detail (LoD), to allow the detection of lesions or other evidence of pathology. Along these lines, a pioneering effort was that of Satava and Lanier, who in 1991 constructed a VR system consisting of HMD, DataGlove, and EyePhones, in which a user could "enter" and "fly through" a 3D representation of an abdominal volume [Sat93]. In this category, virtual endoscopy is among the most advanced applications [Gei95; Sha98], particularly virtual colonoscopy [Hon97]. Endoscopy is used to examine tissue in order to look for macroscopic abnormalities (e.g., ulcers, polyps, tumors, etc.), and is used for many examinations including those of the colon (colonoscopy), stomach, esophagus, tracheobronchial tree (bronchoscopy), sinus, bladder, ureter (hysteroscopy) and kidney (cystoscopy), pancreas, or biliary tree. Virtual colonoscopy is non-invasive, and can be performed using data derived from standard CT and/or MRI scans to reconstruct the organ of interest into a 3D model that permits a fly-through of the lumen [Sat99].

Virtual endoscopic systems typically perspective viewing to accommodate a finite (and relatively small) eyepoint-to-object distance. Using this and other techniques to augment the user's vision during the diagnostic process, several visualization algorithms have been developed [Lor95; Vin97; Nai97]. A notable example of virtual colonoscopy is that being developed by Kaufman and collaborators [You97; Hon95], who have improved on previous approaches based on surface rendering or Z-buffer-assisted volume rendering by using an efficient volume rendering algorithm that is paralleled on a multiprocessor. The approach is illustrated by the sequence of images that appear in Figure 20, showing different views both from the camera viewpoint as well as from an external, global perspective. The figure also illustrates the ability for the user to examine detail, such as a close-up of a detected polyp. In this approach to virtual colonoscopy, the ray-casting method exploits the distance information from each voxel inside the colon to the closest interior colon wall, such that when ray traversal is performed from a particular viewpoint, the distance from the current sampling point to the nearest colon wall is first checked (rather than performing sampling, shading and compositing in the short, regular sampling interval). If this distance is larger than the regular sampling interval, the algorithm jumps by this distance to a new sampling point along the ray. In this manner, the colonic interior can be traversed more efficiently without sacrificing image quality. The main drawback to the technique is the computational cost, an issue that is currently being addressed by this group by considering implementing the algorithm in new volume rendering hardware architectures.

A number of other researchers are also exploring virtual endoscopic methods [Mor98; Nac98; Rub96; Nap96; Sha96; Vin96; Jon96; Lev96]. Importantly, The National Institutes of Health (NIH) and The National Cancer Institute have targeted virtual colonoscopy as the pilot study to compare standard video colonoscopy to virtual colonoscopy for screening for colon polyps and cancer [Sat99].

Published by the Eurographics Association ISSN 1017-4656



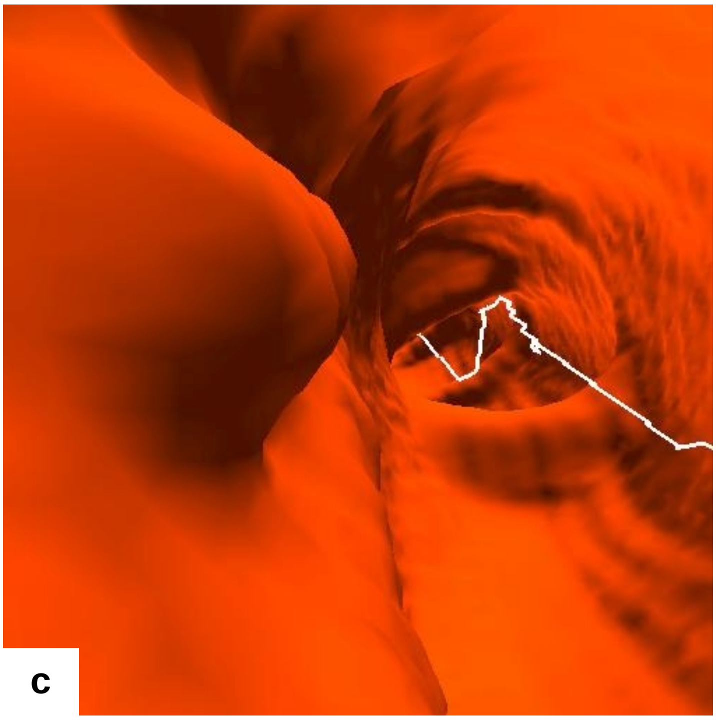


FIGURE 20 Virtual Colonoscopy Based on Volume Rendering. (a) 3D Navigation of a Colon (b) 3D Virtual Colonoscopy of Visible Human Data (c) An 8mm polyp found during a virtual colonoscopy navigation. Courtesy of and copyright 1999 Arie Kaufman, SUNY Stony Brook [Hon95; Hon97; Wan99; You97].

Pre-Operative Planning

Many of the methods used in creating virtual models for diagnostic fly-throughs can be extended to allow the model to be edited, deformed, and/or manipulated. These manipulable models and interactions form the basis of simulation systems that can be used for training and educational purposes, as well as for therapeutic purposes such as pre-operative surgery planning, and rehearsal. Three-dimensional methods can be valuable to physicians in visualizing plans prior to surgery or radiation treatment, and have the potential to contribute toward a more efficient and successful intervention [Sha95; Kik95; Sha98; Van96]. In many applications, the distinctions between pre-, intra-, and post-operative activities are blurred, as the systems that support planning efforts can also aid in guiding the actual surgical procedures as well as in evaluating their outcomes.

One of the most active areas of research is aimed at facilitating neurosurgery and craniofacial surgery planning [Dav90; Lo94; Pom92; Zon89]. A useful and relatively simple approach consists of rearranging the 3D information into different shapes using editing tools, for instance allowing the user to draw curves on the computer screen which can represent virtual cuts into the volumetric dataset, or more generally defining subvolumes and subsequently manipulating or rearranging them [Pfl95; Ney91a; Yas90]. Another type of approach is to create a 3D virtual model that can accurately represent the spatial dimensions and location of the patient's actual anatomy through stereotaxy [Kee96;

Published by the Eurographics Association ISSN 1017-4656

Mol98]. In some cases, a cost function associated with potential damage to critical structure(s) can be defined, such that an "optimal" path and interventional procedure can be determined by minimizing the cost function [Vai97; Kik95]. An important maxillofacial application is facial reconstruction, the main objective of which is to treat congenital or traumatic abnormalities. In most applications, symmetry of the face is assumed such that abnormalities on one side of the face or skull can be reconstructed using a model built up of the normal portion of the face and its mirror image, thus creating a symmetrical model to guide the planning [Alt93; Bil95]. By making this comparison, an accurate reposition or replacement for the malformation can be planned. In the defective area, the corresponding portion of the model can be exported to a computer-assisted design (CAD) and computer-assisted manufacturing (CAM) system that can precisely machine the appropriate prosthesis for implantation. Some current systems use 3D stereolithography to automatically construct a 3D prosthesis directly from CAD/CAM information [Bil95; Neg95]. In work jointly undertaken by the Kent Ridge Digital Labs and the Singapore General Hospital in Singapore, a system is being clinically evaluated for neurosurgery planning using the virtual workbench setup [Ser98].

An excellent example of facial reconstruction is the work of Gross and Roth and their collaborators in the project FACE, aimed at developing precise and reliable methods for facial surgery planning [Rot98; Koc98; Koc96, Koc99]. In this work, a model is created that serves to plan the intervention, predict the results of the intervention, and subsequently compare the results of the procedure. The prediction step is paramount in facial reconstruction, as both patients and clinicians are profoundly interested in the visual results. The approach consists of combining laser-range and CT volume data to create a model of a human face built of prism-shaped elements. Soft-tissue deformations are synthesized using a physically-based, FEM framework, which allows the system to also be used for surgery simulation and training purposes. The pre-surgical model is used to perform virtual surgery, giving rise to a predicted model. This intermediate model serves to visualize the results and to compare the prediction to the original situation. Once the surgical procedure is actually performed, the predicted model is compared with the outcome of the real procedure both visually as well as quantitatively, using error maps of the frontal view contours and three profile outlines. The approach is depicted in Figure 21, which shows a sequence of the pre-operative situation, predicted profile, and post-operative results; the sequence lends itself to quantitative analysis as discussed later. Another example of a maxillofacial application is illustrated in Figure 22, which shows a model constructed to aid in visualizing possible surgical paths that avoid nerve interconnections and other critical structures [Mon99].

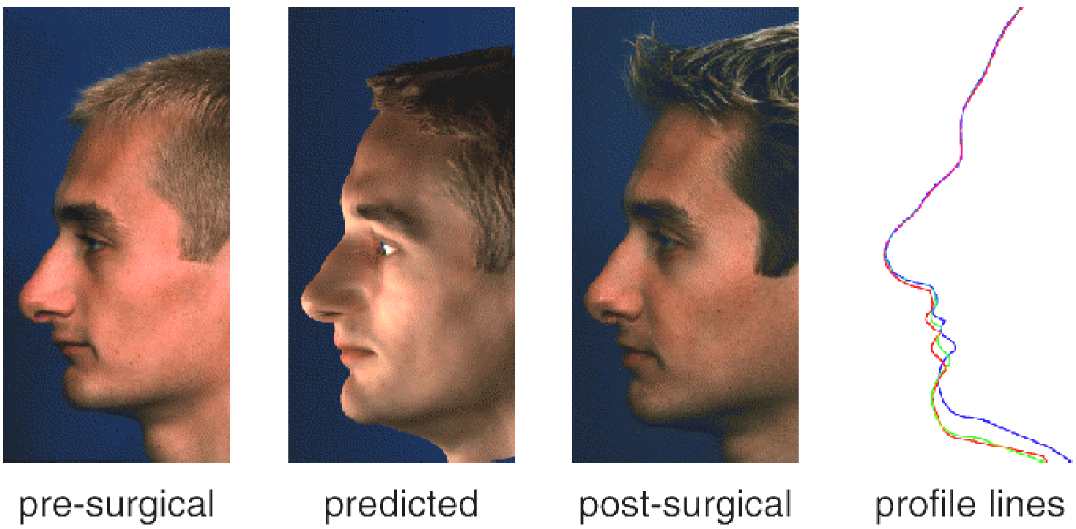
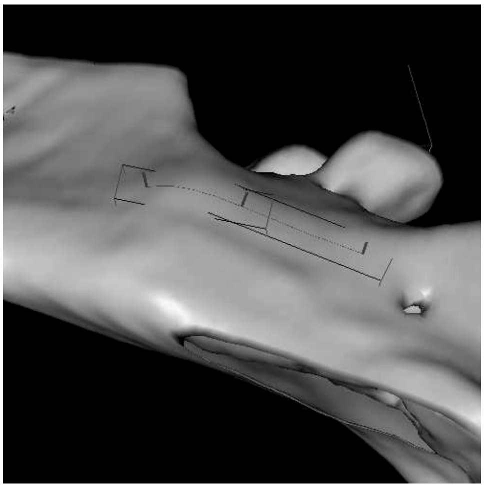


FIGURE 21 The FACE project aims at a new and more reliable method for facial surgery planning based on finite element modeling. The 3D physically-based facial model is reconstructed from CT and laser range scans. Courtesy of R. M. Koch, S. H. M. Roth, M. H. Gross. Swiss Federal Institute of Technology (ETH), A. N. Zimmermann, H. F. Sailer Dept. of Maxillofacial Surgery, University Hospital Zürich [Rot98; Koc98; Koc99].



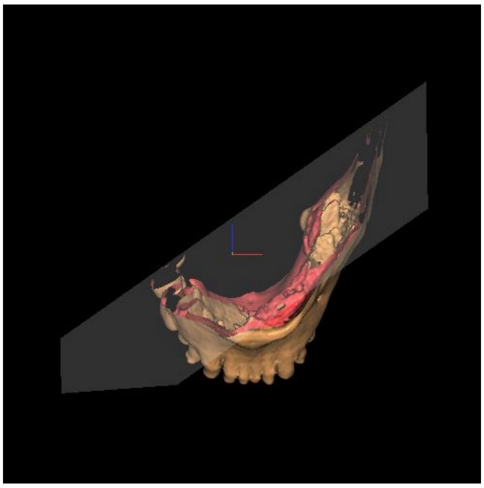


Figure 22 An application to aid in the diagnosis of bone malformations. It is designed to also support surgery simulation and planning. Furthermore it provides the control for a robot to perform high precision osteotomies. [Mon99]

A major area of application is orthopedics [Coh98; Bur86; Oto95; Sut94]. In this domain, 3D models of prostheses are used in conjunction with patient's data to plan the placement of the prosthesis [Dig94; Ho95]. Most of the work has involved hip [Kaz95] and knee replacement [Kie95]. The overall objective is to create both a model of patient structure (e.g., the hip) using CT or other image data, as well as a model of the prosthesis (derived from manufacturer-supplied information), and then use both models to plan (and frequently guide as well as evaluate) the replacement procedure. Examples of this type of work include the robotics-assisted project reported in [Pau92], and hip replacement work as in [Kaz95; Dig98]. In a series of orthopedic surgery-planning projects, Joskowicz and collaborators of the Hebrew University and Haddasah U. Hospital are developing a system for computer-integrated revision total hip replacement (a procedure that is more complex, time consuming, and error-prone than primary hip replacement surgery), and a system that addresses several stages of long-bone fracture reduction including pre-operative planning, nail selection, intraoperative tracking, distal locking, and evaluation [Toc98; Yan98; Jos98; Jos99]. The challenges are numerous, including the requirement of significant skill to perform the procedure; the possibility of incurring position errors and other complications; and the cumulative exposure of surgeons to radiation.

To address these issues, the approach followed by these researchers employs interactive displays of 3D bone models created from preoperative CT studies and tracked (registered) in real time with the overall objective of improving the positioning and navigation accuracy, efficiency, and speed with which planning and interventional procedures can be performed, thereby reducing radiation exposure while potentially improving the outcome of the entire procedure. An illustration is given in Figure 23. The system performs distortion correction and calibration of X-ray units to improve image quality and precision, which are important to properly visualize and align bone structure as well as the model of the nail to be inserted. Using an extension of the Marching Cubes isosurface extraction algorithm, patient-specific 3D geometric models are built of the healthy and broken bones from a sequence of 2D images obtained prior to surgery using CT. Interactively, the surgeon examines the characteristics of the fracture, and determines the upper and lower bone fragments to be joined by a nail (to be selected from a catalog). The system then allows the surgeon to determine the optimal length and diameter of the selected nail by interactively positioning the nail CAD model within the healthy bone model. During surgery, the bone fragment models are used to visualize their relative position. Matching or registering the 3D models created preoperatively with the 2D fluoroscopic images is done using an iterative closest-point optimization method. The approach (which can be used in several applications, including acetabular cup placement, total knee arthoplasty planning and replacement, and systems pedicle screw insertion) is currently undergoing in-vitro testing [Jos98; Jos99].

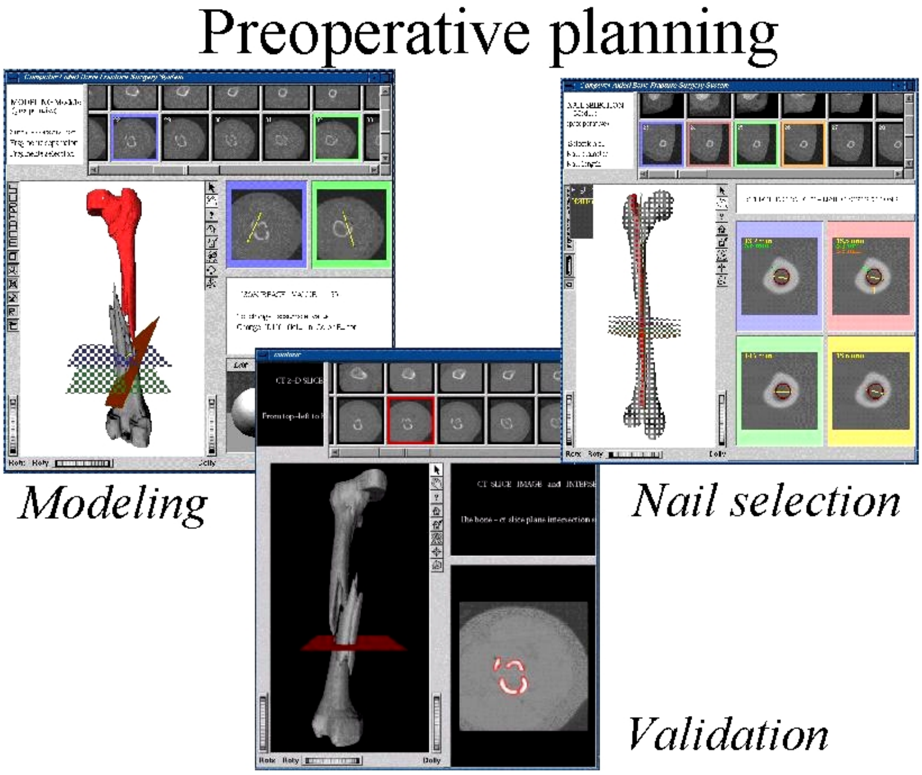


FIGURE 23 A system for computer-aided image-guided surgery of long bone fractures : Preoperative modeling and planning from CT, real-time intraoperative tracking and 2d/3d registration using x-ray fluoroscopic images. Courtesy of Leo Joskowicz [Tok98; Yan98; Jos98; Jos99].

Hepatic surgery simulators are also under development, as in the work of Ayache, Delingette, Montagnat, Soler and collaborators at INRIA in France [Mar98b; Aya98; Cot96; Cot99a; Cot99b; Del98], which was previously discussed in terms of its approach to modeling. Also noteworthy is the ongoing work at the DKFZ in Heidelberg, Germany, led by Meinzer, Glombitza and coworkers [Glo99b]. This is illustrated in Figure 24, which shows a model for volumetric evaluation used in virtual planning of liver resection. Based on the structure of the vessel tree, it is possible to calculate the volume of sound liver tissue which also has to be resected because of devascularization. This analysis is based on the segmentation of the vascular tree. For image data with insufficient vessel contrast, an interactive tool is provided to the user to classify liver segments based on a conventional model of liver segments [Glo99b]. The same group is also investigating methods for craniofacial applications, as shown in the stereo image of Figure 25.

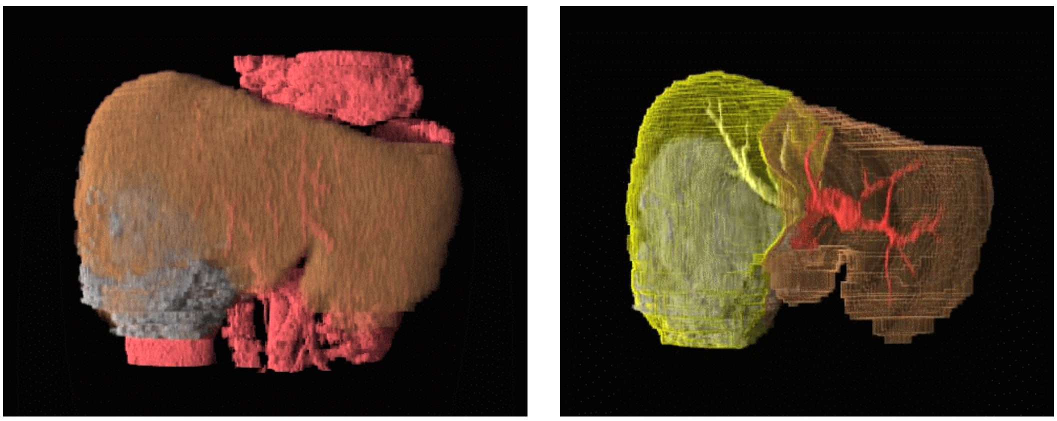


Figure 24 Computer aided surgical planning of liver resections. (a) The liver (brown) is shown together with a tumor (grey) and the neighboring organs and veins (red) (b) symbolic description of the vessel trees which enables surgeons to estimate the volume of resected sound liver tissue. Courtesy of Gerald Glombitza, DKFZ Heidelberg, Germany [Glo99b; Glo98a; Glo98b].

Published by the Eurographics Association ISSN 1017-4656

Figure 25 Stereo image of a cut-away skull for red/green glasses. Courtesy of the Medical and Biological Informatics Group, DKFZ Heidelberg, Germany.

Planning also plays a crucial role in radiation therapy. Radiation treatment requires careful path-planning to determine the optimal geometry and dose distribution [Tom96]. As with other pre-operative planning methods, a cost function associated with damage to critical structure is defined, such that a minimization of this cost function can yield an optimization of the plan [Sch95; Tom96]. The 3D visualization of target volume critical structures, beam dose calculations, and simulated radiation dose distribution can provide the framework for treatment plan optimization. These and other issues are being investigated in current research on conformal radiation treatment planning [Kes94], iterative optimization [Sch93], time-dose planning [Sch94], system positioning calibration [Had98] and treatment setup verification [Ban98b].

Simulation and Rehearsal

This is one of the most active areas of research in medical imaging, as revealed in the recent literature (see, for instance, [MIC98; Tay96; Tay95; Sof98]). In the early 1990s, prototype systems were created for such applications as tendon transplant simulation [Del92] and internal organ (stomach, colon, pancreas, gall bladder and biliary tree) manipulation [Sat93]. Both used HMDs and DataGloves as interaction mechanisms although the models were not deformable in the same sense as the term currently implies. A basic type of morphing was performed to demonstrate the viability of tissue non-rigidity [Mer95], which represented one of many attempts that began to explore soft tissue modeling. In this regard, finite element models represents one of the most commonly used approaches. An interesting current application centers on endoscopic sinus surgery simulation using the endoscopic instrumentation, a physical mock patient head that contains electromechanical mechanisms that provide forcefeedback, and haptics [Edm98; Wie97; Edm97]. In another application, a hysteroscopy simulation system is under development which can integrate visual and haptic input with patient-specific CT data, and allows different virtual procedures to be performed in order to improve the overall intervention plan [Lev96]. Other surgery simulation applications include opthalmology [Hun95], arthroscopic knee surgery [Gib97], cephalopelvic distortion [Gei92], birth delivery [Pro97a], and trunk respiration simulation [Pro97b], among others [Rho97; Sha98].

Psychiatry and rehabilitation are areas where simulation environments can also have a considerable impact. In particular, immersible environments are emerging as possibly useful elements in the treatment of phobia, such as acrophobia (fear of heights), where patients are placed in virtual environments that recreate situations that induce acrophobic anxieties (e.g., elevators, suspended bridges, etc.). By incrementally increasing either the sense of presence or the severity of the perceived situation (what is called graded exposure), cases have been reported in which subjects were successfully treated for these anxieties [Lam94; Hod95; Rot95]. Another line of research considers the notion of "empathy" wherein a subject, through an immersible environment, attempts to better understand the limitations or emotions of others

Published by the Eurographics Association ISSN 1017-4656

who may be suffering from disabilities, impairments or other conditions that may cause, for instance, visual disturbances, fatigue or other physical limitations [Sat99]. In rehabilitation, an interesting application consists of the creation of a "virtual world" in which patients who are going to need a wheelchair for locomotion can adapt to the notion of moving in this manner by moving about in various virtual environments [Gre94].

Education and Training

As flexible visualization and modeling methods continue to improve, the traditional use of text, images and cadavers for educational purposes can be complemented with virtual models and simulation systems that can support various forms of interactive explorations [Mel97; Rai98]. An example of an educational application using deformable tissue models is the project ARTIST, which is being developed as a real-time surgery trainer by Gross and collaborators [Bie98]. The overall objective of this activity is to create a system that provides interactive manipulation of high-resolution 3D models using a haptics interface. The emphasis is placed on both the formulation of efficient representations of the underlying anatomical structures with deformation properties, and also on the efficient computations to provide real-time dynamic deformations and feedback. The geometrical representation is achieved using common tetrahedralization methods to create a model, combined with texture mapping to enhance the visual realism. The collisions between the tetrahedra and the virtual scalpel are calculated using a local collision-detection algorithm, and the underlying dynamics are expressed using a system of masses and springs attached to each tetrahedral vertex and edge, respectively. Relaxation is performed using hierarchical Runge-Kutta iteration by traversing the data structures in a breadth-first order. Current investigations center on improving computational efficiency, especially during cutting procedures.

Other examples of educational and training systems are hypermedia [Tre98b] and knowledge-guided methods in support of neuroanatomical studies [Hof95; Pfl98; Tog96; Mon93]. Many of the simulation systems cited previously are used for surgery training in addition to surgery planning, such as those reported in [Edm98; Rot98; Cot96]. At present, the emphasis seems to be placed on computational efficiency to improve the level behavioral realism, and, unfortunately to a lesser degree, efforts concerned with usability issues, such as the work reported in [OTo98].

6.3 INTERVENTIONAL GUIDANCE AND SUPPORT

A number of intra-operative and real-time support interactions have been under development during the past several years. These interactions take advantage of improvements in real-time sensors (both image-acquisition and 3D digitizers), image-registration techniques, and robotics, giving rise to specialty subareas variously known as image-guided surgery, computer-aided surgery, computer-assisted intervention, medical robotics [Ada90; Tay96].

Intra-Operative Guidance and Navigation

Intra-operative systems can be designed to deliver different types of assistance. In some cases, the system can be used as a calibration or checking mechanism, to determine whether preoperative plans are being followed [Cin95; Nol95]. In other cases, the system might offer real-time guidance for actually performing the intervention, possibly including robotics assistance [Jos98; Van96; Vai97]. In other applications, the interaction aids in conducting some sort of exploration or evaluation during the intervention [Des95]. Once again, it is seen that pre- and intra-operative (and some times even evaluation) functions meld together. One of the most common characteristics of intra-operative guidance and navigation system is that they generally use some type of pre-operative information (plans, images, models, and/or video) which is correlated with the information obtained during the intervention [Gri98; Gri95; Gut91; Ban98b].

In general, the objective is to create pre-operative 3D models (from CT and MR data, for example) which display structures and abnormalities of interest. The models are then provided to the surgeon during the intervention to aid in localizing and extracting targeted tissue with minimal damage to critical structures. To improve pre- and intra-operative registration, stereotactic methods have traditionally been employed [Mac94; Kee96; Mol98]. Although stereotactic frame-based approaches remain the most well established surgical procedures, some techniques recently have been suggested to obviate stereotaxy [Gri96; Tom96; Gri95]. Frameless methods based on physical space localization include articulated mechanical arms, ultrasonic range-finding systems, electromagnetic systems, and active and passive optical techniques [Hem92; Wat95; Smit94; Mau98; Gri96]. To match the 3D models constructed from the pre-operative data with the 2D images that the surgeon actually sees during the procedure, a number of methods are under investigation, such AR methods for overlaying structures in the surgeon's field of view [Gri95].

An application area where intra-operative methods are actively being developed is neurosurgery. One example is the clinical system that has been under development for a number of years by a group of researchers at the Massachusetts Institute of Technology, Cambridge, USA [Gri98]. The aim is to develop a high-precision image-guided system composed of imagery, registration, tracking and visualization subsystems. The performance of the system is currently being assessed clinically. Another example is a surgical navigation system used in pediatric epilepsy surgery [Cha98]. There are numerous systems under development applied to orthopedics, such as the previously discussed image-guided system that aids in pre- and intra-operative hip-replacement [Jos99] (see Figure 23), as well as other prostheses-related applications [Coh98; Dig98; Ho95]. There are a number of challenges associated with intra-operative navigation and image-guided surgery. A major consideration is accuracy, which is related to the number and types of errors that are associated with the methods [Mau98], registration accuracy, and real-time response, some of which are being addressed in current investigations [Gri98; Cha98; Moo98]

Robotics-Assisted Intervention

Closely associated with the concept of image-guided intervention is robotics-assisted intervention, where the electromechanical accuracy of robots can be exploited to perform tasks such as precisely controlling the positioning of instrumentation, or guiding the user in making movements [Pau92; Tro96]. As a result, robots are programmed to perform specific tasks prior to surgery, or can also be designed to dynamically adapt to the environment or user. In some applications, the robotic subsystem actually performs part or all of the surgical procedure, as the resulting precision can be useful in certain cases such as stereotactic neurosurgery [Mas98], and to perform minimally invasive tumor biopsies [Gla95].

A number of medical robotics systems have been applied to orthopedics [DiG94; DiG98], including such applications as hip [Kaz95] and knee replacement [Ho95]. Another important application area is laparoscopy [Kob98]. In this area, one interesting investigation attempts to compare human and robotic performance in force controlled organ retraction [Pou98b]. Meanwhile, other efforts are centered on servoing considerations laparoscopic instrumentation control issues [Fin95], as well as telelaparoscopic experiments [Tay95]. Robotics-based methods are also being explored in microscope control [Gio95], in calibrating video cameras in radiation therapy [Had98], and in studies that address safety considerations [Cai93].

6.4 REMOTE INTERACTIONS

One of the most main opportunities and challenges in healthcare is the possibility of establishing remote links to send, receive, or communicate about, all kinds of clinical information. In medical imaging, possible applications range from the transmission of compressed imagery (and other data) in teleradiology [Eve99] to the concept of performing therapeutic interventions in image-guided telesurgery [Sat99]. A few promising examples are outlined below.

Teleradiology and Telecollaboration

To take advantage of the increasingly ubiquitous and powerful "information highways" that connect a growing number of users and centers throughout the world, a number of noteworthy projects and initiatives are underway. A notable example in this context is the work of Marsh, whose efforts concentrate on the standardization of web-based medicine [Mar99; Mar98c]. A depiction of these efforts is shown in Figure 26. One of these is the proposed standard based on web technology called "Virtual Medical Worlds (VMW)" aimed at providing an organizational structure of medical information as well as a possible framework for integration diverse types of information into future medical information systems [Mar98c]. The general VMW design is based on hypergraphics and hypertextual qualities of VRML and HTML as a navigational medium to remotely access multi-media information systems, and web-based languages such as Java to initiate visualization, processing and other non-web based functions. Hence, the World-Wide Web (WWW, or simply the Web) can be used as the interconnective glue between all aspects of a telemedicine society [Mar99]. Significantly, the large majority of the necessary middleware support standards and protocols, as well as the technology, already exist, while bandwidth capabilities continue to improve.

An illustration of collaborative work is the project undertaken by the National Cancer Center Hospital in Tokyo. At that institution, researchers are developing a VR-based surgical conference system that incorporates video cameras and simulates virtual organs and tumors (enhanced with textures) viewed through a head-tracked display, and supports surgical procedures performed on models created from patient-specific CT and MR data such that the internal structure of the organ is visualized as the simulated resection takes place [Sof98].

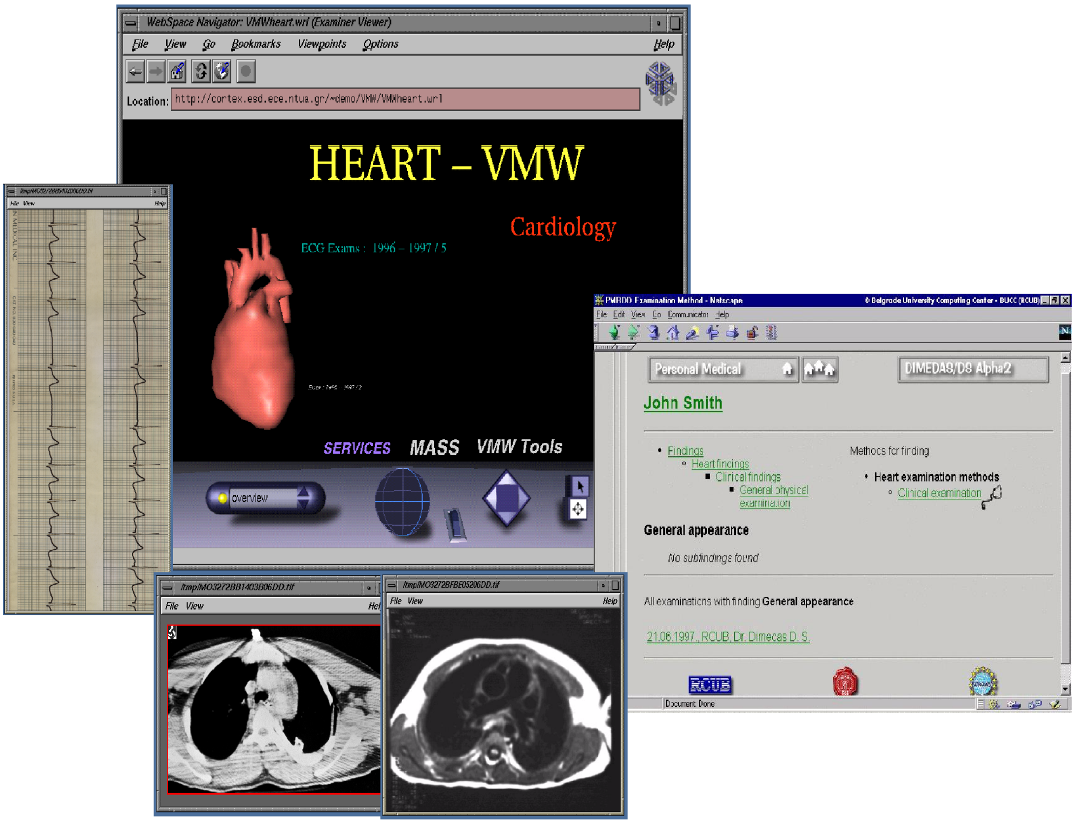


Figure 26 VMW is a global standard based on web technology to organize existing medical information and to provide the foundations for integration into future forms of medical information systems. It utilizes VRML and HTML as a navigational medium to remotely access multimedia information systems, and JAVA to initiate visualization, processing, and non-web based packages. [Mar99; Mar98c]

Other teleconferencing and telecollaborative projects are those reported in [DeB96] and [Kli95].

An exemplary case of an advanced teleradiology application is the CHILI project headed by Engelmann, Meinzer and collaborators [Eng98a; Eng98b; Eng98d]. Some of the salient features of this project are security compliance [Eng97a; Eng97b], visualization support [Eve99], extensibility supported by a plug-in mechanism [Eng98c], platform independence [Eng98c], and wavelet-based image compression [Eng98a]. The system supports access to the CHILI DB via WWW access for the distribution of images through the Internet, such that images can be presented and processed in cooperative or collaborative teleconferences. An example of a CHILI interface is shown in Figure 27.

Currently, the system is in clinical routine in more than 40 medical centers, and has distributed over 250,000 images, and some users in Germany and the US are developing image analysis and visualization applications for subsequent plug-in integration [Eng98a; Eve99]. Efforts are underway to develop a platform-independent version in Java.

As these examples indicate, some advances are being made in the creation and implementation of useful clinical applications. However, progress has been uneven, especially at the international level, where advances have been hindered by such issues as information security, the absence of globally established standards, the lack of sufficiently potent infrastructures at different levels, and financial concerns [Mar99]. Perhaps a greater number of cases that have successfully overcome these limitations at a regional level, coupled with more concerted efforts at the international level, can serve to address these challenges.

Published by the Eurographics Association ISSN 1017-4656

FIGURE 27 Figure 27 CHILI is a Tele-radiological workstation and is used in more than 40 medical institutions. Images are distributed between different sites for the purpose of interpretation and consultation. The digital images can be presented, analyzed and discussed simultaneously. Courtesy of Uwe Engelmann, DKFZ Heidelberg, Germany. [Eng98A; Eng98B; Eng98D; Eng98E; Eve99].

Telesurgery and Remote Interactions

Telepresence in surgery may be a potentially important application in emergency situations when the patient cannot be easily or sufficiently quickly transported for treatment, or in cases where the preferred clinical expert is located far away, or in scenarios that involve risk to the surgeon [Sat95]. A possible architecture for telesurgery systems consists of a control console at the surgeon's location connected via a combination of links (Internet, satellite, etc.) to a surgical unit at the patient's location. In this type of set-up, the surgeon can interact with the patient avatar (or a virtual model of part of the patient's body) using visual, auditory, tactile and force feedback, such that the surgeon's movement of end-effectors at this location direct the actions of the corresponding end-effectors at the remote location in a "master" and "slave" manipulation framework [Sha98]. Examples of similar systems are found in [Gre95] and [Sas96].

At present, no remote telesurgery procedures have been performed on patients, although some "local" telesurgery procedures have been performed in the same room as the patient [Mar98b; Sat99]. In 1997, Himpen and collaborators performed what may well be the first telesurgery gall bladder operation on a patient, followed by other procedures such as Nissen fundoplication and arteriovenous fistula construction [Him98]. The same system was later used for perform over 150 successful heart operations [Sat99]. Margossian and collaborators have recently performed a reanastomosis of a fallopian tube using the Zeus system [Mar98a]. In addition, telesurgical experiments have also been conducted in laparoscopic cholecystectomy [Him98] as well as in surgical training [Fen98] and micro-surgery applications [Mit95].

An intriguing application of remote medical interactions is the Everest Extreme Expedition (E3) project, a multinational and inter-institutional undertaking that aims to establish the first telemedicine clinic that links a remote, harsh environment (Mount Everest) with investigators from several major medical and research institutions. Project information can be obtained from [EVE99ONL], and an illustration of the visualization interface presenting some of the relevant medical information associated with this project is given in Figure 28. Current project objectives include providing medical support at a base camp to the expedition team, performing real-time monitoring of vital signs (e.g., heart and respiratory rates, oxygen saturation, body temperature, etc.), and assessing the effects of high altitude physiology. This project will thus test frontier capabilities in telemedicine and telecommunications technologies.

The limitations to telesurgery and other remote interactions are numerous. In addition to the difficulties mentioned above related to teleradiology and teleconferencing applications (e.g. security, bandwidth requirements, the lack of standards, etc.), telesurgery would additionally require accuracy, precision and real-time response over long distances and through various layers of networking interconnections. Some of these issues are currently being addressed, as reported in [Sat99]. However, although the interest is relatively high and the potential benefits may be significant, the field is largely in its nascent stages, and clearly more work is needed at various technical, political and financial fronts [Mar99].

6.5 ASSESSMENT AND PREDICTION

It is important to objectively assess the performance of any system in order to better understand its performance strengths, and limitations, as well as to demonstrate overall utility.

Pre- and Intra-Operative Evaluation

As observed earlier, an interesting approach to evaluation is the utilization of pre-operative plans as a means of system calibration prior to intervention, while another useful approach consists of using pre-operative plans during intervention to determine whether surgery proceeds according to plan [Cin95; Nol95]. In educational and training settings, some activities center on evaluating simulation systems that use FFB haptics devices [OTo98], as well as on validating systems designed to support facial reconstructive surgery [Bie98]. In other instances, simulation systems are assessed by directly integrating them into the clinical environment from project inception, as in the case of the hepatic surgery application reported in [Glo99b].

In image-guided therapy, a number of studies are underway to clinically evaluate systems designed for applications to craniofacial surgery [Gri98; Cha98], facial surgery [Koc98; Koc99; Rot98], and orthopedic surgery [Moo98; Toc98]. Systems designed for other therapeutic applications, such as graded-exposure VR environments used in phobia treatment, employ evaluation methods based on psychological studies [Hod95]. Similarly, robotics-based systems designed for a variety of applications are currently being evaluated clinically [Dig98; Tro96], including performance comparisons between humans and robots [Pou98b], and assessment of relevant safety issues [Cai93].

Post-Operative Assessment

In general, virtual models and registration methods used in image-guided intervention are difficult to quantitatively evaluate, since there are no "gold standards" or well established benchmarks. The use of synthetic data phantoms, or reference objects can serve as valuable aids in numerically evaluating models [Cha98]. An example of the use of synthetic data is given in [Pou98a], where a method for tracking brain white matter fiber bundles in diffusion tensor maps using a Markovian model is evaluated using synthetic tensor images.

An illustration of the use of quantifiable measures for post-surgery evaluation is the facial reconstruction approach described in [Rot98; Koc98; Koc99]. In this application, the system used for surgery simulation and planning generates a series of profile lines of the face that can be compared with the corresponding contours of the patient profile after the surgical procedure has been performed through a series of error maps. An example of the use of reference objects in evaluation is provided in metallic stent-graft placement to repair thoracic aortic aneurysms, as reported in [Rub96; Sha96]. Similarly, stent placement facilitates post-operative assessment in endobronchial procedures [McA96].

As suggested in the foregoing discussions, it appears that most groups are evolving from the first stages of system development into system testing and evaluation phases. Despite these evaluation efforts, however, there still seems to be a need to undertake rigorous tests involving statistically significant numbers of patient cases, multi-center trials, and other clinically well accepted validation methods coupled with usability testing. Development of more widely agreed-upon benchmarks, especially in the context of complex interaction mechanisms or the creation of virtual models, are also needed.

7. CHALLENGES AND OPPORTUNITIES

In this paper, a snap shot of the field of medical imaging has been given, focussing on current methods and trends that characterize the state of the art. As the discussions suggest, progress in the field has been significant over the past few years. This section briefly summarizes some of the most significant advances and trend, placing the emphasis on outstanding challenges that merit further investigation.

Trends and Achievements

The accomplishments that have taken place in medical imaging over the last few years have been numerous and influential. First, estimable achievements have been made in the development of imaging acquisition techniques (e.g., functional and tagged MRI, 3D ultrasound, and spiral CT, among others). Importantly, scanning system manufacturers have increasingly supported open architectures, thereby fostering the use of off-the-shelf components and software subsystems. Newer trends, including microsurgery [Lev98b], promise to further redefine the type of imagery that can be acquired. Another important step forward has been the creation of reliable and widely accessible data (most notably the Visible Human dataset and anatomical Atlases), coupled with the invention of useful volume visualization algorithms. These and other advances have spurred further innovations, including the development of methods both for integrating different types of data (e.g., intra-modality correlation, multimodality fusion, 3D-to-2D image registration, etc.), as well as for presenting complex information using multimedia, multidimensional approaches, and the availability of several general-purpose medical software systems for interactively visualizing 3D image data.

In addition, progress in related areas have also made substantial impact on medical imaging. In particular, advances in computer hardware, peripheral devices that enhance perception, and common software tools and libraries have all been instrumental in pushing the frontiers of the field. Moreover, increasingly ubiquitous global telecommunications capabilities (i.e., the Internet and the WWW) have certainly helped to promote telemedicine initiatives while at the same time providing an important means for researchers (and organizations) to more easily communicate and exchange information and data. Similarly, progress in more basic scientific and mathematical fronts have both contributed to, and benefited from, medical imaging research. Notable examples are wavelet and multiscale representations, models and simulations based on dynamic formulations, mathematical morphology, probabilistic techniques, and approaches based on artificial intelligence (including knowledge-based, connectionist, and fuzzy-set theoretical methods), to name a few. Furthermore, HCI principles and techniques have increasingly been integrated into the overall UI design process.

Challenges and Opportunities: **A "Top 10" List**

These advances are poised to possibly qualitatively change, and ideally improve, the nature of health care. In practice, however, the advances largely remain in developmental stages, and extensive clinical testing and evaluation is certainly required. With this in mind, a list of outstanding challenges and opportunities can be defined:

1. Validation and Evaluation

Clinically, the overriding challenge -and obligation- is the extensive evaluation of each application. This clearly is not a new concept: the need for clinical validation and evaluation has always been there. However, novel ideas should rigorously and convincingly demonstrate that, for instance, a certain visualization actually improves diagnostic accuracy, or that a particular interaction mechanism reduces users' cognitive and visual workloads. Although many ideas are attractive and intuitively convincing, they nonetheless remain unproven hypotheses unless they are tested and validated. In this regard, a number of well established evaluation methods should be more frequently used (e.g., using phantoms, quantitative comparisons with benchmarks and gold standards (when available), ROC analysis, retrospective and prospective studies, and biostatistical experimental design studies that include statistically significant test cases).

2. Clinical Integration

Closely associated with clinical evaluation is the concept of integrating the results of research directly into the clinical environment. In fact, evaluation and integration may sometimes be indistinguishable. In general, however, the results of the research activities must be integrated into the clinical setting at the earliest possible stage in order to insure user acceptance and routine clinical use. Here, too, a number of well known approaches can be invoked, including multicenter trials and possibly governmental or organizational approval mechanisms.

3. User-Centered Design and Usability Testing.

It has been pointed out -and emphasized- several times in this report that perhaps the most important design component is the user interface. Although clinical evaluation is an imperative to demonstrate such basic characteristics as accuracy, reliability and robustness, user-centered design and usability testing are equally important in determining whether the system will in fact be used at all. Hence, from the very starting point of any project, well established HCI principles and methods must be used, stressing task analysis, workload reduction, user-centered design and usability studies, which call for a continuous iterative cycle of design-testing-redesign.

4. Segmentation

No list of open problems would be complete without this old nemesis. Although a number of working solutions exist, we simply have not solved this problem (at least not in a fundamental, scientific sense). Perhaps a different formulation of the problem may be needed. It may be that practical solutions can be formulated through a combination of currently available methods, application-oriented considerations, and some degree of user interaction. A less ambitious though perhaps more immediate problem is that of duplication: a glance at current literature will quickly reveal that most groups are probably using very similar (if not exactly the same) methods to handle a wide spectrum of segmentation problems. It would be greatly beneficial to community to create generally available libraries of algorithms whose design would permit their implementation in different platforms.

5. Computational Efficiency and Reusable Software

The equation that interrelates accuracy, precision, computational efficiency, and platform independence has become increasingly complex over the past few years. The emergence of mathematically elaborate modeling methods, the proliferation of sophisticated (and heterogenous) interaction devices, the desire to create anatomically accurate virtual models, and the need to reduce perceived system response are some of the main contributing factors. A related subject is the creation of reusable drivers and middleware which can be made available to researchers using the same types of platforms and environments. These issues do not so much constitute a single problem to be solved in one fell swoop, but rather an ever-present and continuing challenge in terms of algorithmic efficiency, some standardization, and software engineering considerations.

6. Widely Available Databases

The Visible Human project set the stage for realizing the usefulness of high-quality, widely available data. By serving as a sort of de facto benchmark, the project also hinted at the advantages of establishing some type of standards in the creation and dissemination of useful information and virtual models. Both researchers and clinicians will benefit from similarly well organized initiatives. This goal, of course, presents a number of concomitant challenges, such as transmission-related issues, the need to create appropriate intuitive interfaces, efficient search engines and indexing mechanisms, and addressing problems related to the digitization, standardization, security, confidentiality and general accessibility of clinical records. These may be formidable challenges, transcending the technical arena into financial and political domains. Nonetheless, many of these difficulties will have to be at least partially overcome in order to make high-fidelity digital data more easily available. Frontier research thrusts in medical imaging can be viewed as a positive forcing function in this regard, although a more concerted organizational effort is certainly needed.

7. Use of the Internet

Ever expanding telecommunications and networking capabilities have not only enabled the exchange of data and other types of information within the community, but have also established useful and timely means of communication among researchers and organizations throughout the world. However, these mechanisms have not been fully exploited by the community as a whole. For instance, communications media could be used to provide a variety of educational materials (e.g., courseware, self-help teaching aids, tutorials, etc.), organized informational services (e.g., current listings of ongoing events, on-line repositories of software and peripherals vendors, pointers to "hot topics" such as the latest advances in imaging systems, domain-specific search engines, etc.), communications services (e.g., teleconferencing and CSCW tools, or other types of supports for collaborative purposes), and research supports (e.g., algorithms for compression, segmentation, registration, or applets for interactively visualizing data remotely, etc.). A number of professional and/or international organizations are beginning to provide some of these services and materials, although a series of parallel, focussed and highly organized activities would have a better overall impact.

8. Prognosis and Outcomes Analysis

As virtual models and simulation systems become more accurate and reliable, it may become possible to extend the notion of planning, guidance and evaluation to include prognosis and outcomes analysis. For instance, it is possible to envision a simulation system that can support virtual surgery such that intermediate (and ideally long-term) effects of therapy can be quantitatively predicted. Such a system might be useful in exploring "What if" scenarios from a clinical perspective, and could also prove to be valuable educational tools. The technical challenges are considerable, such as the formulation and validation of physiological models that can accurately forecast the evolution of disease or the effects of therapy, the creation of methods (possibly using case-based approaches) that can present possible outcomes given different treatment strategies, novel visualization methods that can capture and present these evolutionary processes, and the underlying epidemiological studies on which the predictions and outcomes would be based.

9. Cost Consideration

As has been pointed recently [Sat99; Rho97], one of the clear trends in health care today is a careful and frequent assessment of the so-called cost-benefit ratio associated with any medical activity, including research. Hence, it remains somewhat of a challenge to demonstrate that these advances would actually translate into tangible improvements in terms of reliability, efficiency, cost and overall quality of health care, from the viewpoint of the patient, the clinician, and the health care organizations (private and public) that are eventually financially responsible. From a research perspective, however, it is difficult and perhaps even counterproductive to place the cost-benefit ratio as the overriding principle guiding the scientific efforts. In many cases technical progress is neither inspired nor diminished by cost considerations. Thus, in our opinion the challenge does not lie in imposing a cost-benefit ratio on research in general, but rather on identifying how or when (or whether) to do so.

10. Reality Checks

Lastly, it seems that many of the foregoing challenges might be summed up in the KISS principle: "Keep It Simple, Stupid." Importantly, it should be recognized that simplicity does not preclude creativity, mathematical elegance or scientific rigor - in fact, in most cases the simplest possible theory is the correct, most elegant, and most creative one. Simplicity should also not be confused with being simplistic, as what is sought is the simplest possible solution to a problem, not just the simplest solution. Hence, many of the challenges presented herein, spanning such wide-ranging issues as computational complexity, the degree of presence, patient comfort, etc., all call for scientific integrity combined with a measure of common sense.

8. WEB SITES

```
http://euromed.iccs.ntua.gr
http://www.hoise.com/vmw
http://www.cs.sunysb.edu/~vislab/projects
http://www.cise.ufl.edu/~vemuri
http://www.vismed.at
http://www.tiani.com
http://www.cg.tuwien.ac.at
http://www.medcom-online.de
http://3dheartview.iccs.ntua.gr
http://www.igd.fhg.de/www/igd-a7
http://mbi.dkfz-heidelberg.de
http://www.chili-radiology.de
http://www-sop.inria.fr/epidaure
http://iacl.ece.jhu.edu/projects/gvf
http://www.univie.ac.at/morphology
http://www.uke.uni-hamburg.de/institute/imdm
http://www.cs.huji.ac.il/~josko
http://www.cg.inf.ethz.ch/~roth/face/
http://www.cg.inf.ethz.ch/~bielser/artist/
http://kogs-www.informatik.uni-hamburg.de/PROJECTS/imagine/Imagine.html
http://www.chili-radiology.com
http://mbi.dkfz-heidelberg.de/mbi
http://everestextreme99.org
http://www.univie.ac.at/morphology
```

9. ACKNOWLEDGEMENTS

We would like to thank the following colleagues who have contributed to this paper:

Nicholas Ayache
Hervé Delingette
Uwe Engelmann
Gerald Glombitza
Eduard Groeller
Markus Gross
Karl Heinz Höhne
Leo Joskowicz
Arie Kaufman
Andy Marsh
Hans-Peter Meinzer
J. Montagnat
Andreas Pommert
Jerry Prince
Karl Rohr
Martin Roth
Georgios Sakas
Richard Satava
Siegfried Stiehl
Johannes Streicher
Demetri Terzopoulos
Jay Udupa
Baba Vemuri

FACE project

The Face project is partially funded by the Swiss National Science Foundation (SNSF) under grant no. 2153-049247.96/1.

VisMed project

The work at the ICG Vienna has been funded by the VisMed project VisMed is supported by Tiani Medgraph, Vienna, and by the Forschungsfoerderungsfond fuer die gewerbliche Wirtschaft (FFF), Austria

Euromed project

Euromed project was supported by the European Commission ISIS'95 programme.

10. REFERENCES

[Ack98] J. M. Ackerman. The Visible Human Project Proc IEEE 86:504-11, 1998.

[Ada90] L. Adams, W. Krybus, Dietrich Meyer-Ebrecht, R. Rueger, J. M. Gilsbach, Ralph Moesges, G. Schloendorff. Computer-assisted surgery. IEEE Comput. Graphics Appl., 10(3):43-51, 1990.

[Agr93] R. Agrawal, T. Imielinski and A. Swami, Mining Association rules between sets of items in large databases, Proc. 93 ACM SIGMOD Int. Conf. on Management of Data, pp. 207-216, Washington, D. C. May 1993).

[Ake93] K. Akeley, Reality engine graphics, in Proc. SIGGRAPH'93, Anaheim, CA, 1993, pages 109-116.

[Ale56] P. Aleksandrov, Combinatorial Topology, Vol. 1, Gralock Press, Rochester, NY (1956).

[Alt93] D. Altobelli, R. Kikinis, R. Mulliken et al., Computer Assisted three-dimensional planning in craniofacial surgery, Plastic Reconstruct. Surg. Vol. 92, pp. 576-584 (1993).

[Ami98] A. Amini, P. Radeva, M. Elayyadi, and D. Li, Measurement of 3D Motion of Myocardial Material Points from Explicit B-Surface Reconstruction of Tagged MRI Data, Proc. 1998 Medical Image Computing and Computer-Aided Intervention (MICCAI 98), Springer Lecture Notes in Computer Science 1496, pp. 110-129 (1998).

[Ata95] L. K. Atata, A. P. Dhawan, J. P. Broderick, M. F. Gaskil-Shipley, A. V. Levy, N. D. Volkow. Three-dimensional anatomical model-based segmentation of MR brain images through principal axes registration. IEEE Trans. Biomed. Eng., 42(11):1069-1078, 1995.

[Aus92] P. Ausher, G. Weiss and M. Wickerhauser, Local sine and cosine bases of Coifman and Meyer and the construction of smooth wavelets, in Wavelets - A Tutorial in Theory and Applications, vol. 2., Wavelet Analysis and its Applications, C. K. Chi, ed., Academic Press, San Diego, pp. 237-256 (1992).

[Avi92] R. S. Avila, L. M. Sobierajski, Arie E. Kaufam. Towards a comprehensive volume visualization system. In Proc. VISUALIZATION'92, pages 13-20, Boston, MA, 1992.

[Aya93] N. Ayache, A. Gueziec, J. P. Thirion, A. Gourdon, J. Knoplioch. Evaluating 3D registration of CT-scan images using crest lines. In Mathematical methods in medical images, San-Diego, USA, Jul. 1993. SPIE-2035-03.

[Aya95a] N. Ayache, P. Cinquin, I. Cohen, et al., Segmentation of complex three-dimensional medical objects: A challenge and a requirement for computer-assisted surgery planning and performance, in Computer-Integrated Surgery, R. Taylor et al., eds. Cambridge, MA: MIT Press, pp. 59-74 (1995).

[Aya95b] N. Ayache, editor. First international conference on computer vision, virtual reality and robotics in medicine, CVRmed'95, Nice, France, Apr. 1995. Springer-Verlag. Lecture Notes in Computer Science.

[Aya97] N. Ayache, S. Cotin and H. Delingette, Surgery simulation with visual and haptic feedback, 8th. International Sump. of Robotics Research, Y. Shirai and S. Hirose, eds.; pp. 311-316, Springer; Japan (1997).

[Aya98] N. Ayache, S. Cotin, H. Delingette, J-M Clement, J Marescaux, M. Nord, Simulation of Endoscopic Surgery, Journal of Minimally Invasive Therapy and Allied Technologies (MITAT), July 1998.

[Azu97] R. T. Azuma, A survey of augmented reality, Presence:Teleoperators Virtual Environ. Vol. 6, No. 4, pp. 355-385 (1997).

[Bah90] H. Baher, Analog and Digital Signal Processing, J. Wiley (1990).

[Baj83] R. Bajcsy, R. Lieberson, M. Reivich. A computerized system for the elastic matching of deformed radiographic images to idealized atlas images. Journal of Computer Assisted Tomography, 7(4):618-625, 1983.

[Bal82] D. Ballard and C. Brown, Computer Vision, Prentice Hall, Englewood Cliffs, New Jersey (1982).

[Ban98] R. Bansal, L. Staib, Z. Chen et al., A Novel Approach for the Registration of 2D and 3D CT Images for Treatment Setup Verification in Radiotherapy, in Medical Image Computing and Computer-Assisted Intervention (MICCAI) 98; pages 1075-1086; Cambridge, MA, Springer Lecture Notes in Computer Science 1496 (1998).

[Bar93] C. Barillot, Basic Principles of Surface and Volume Rendering Techniques to Display 3D

Medical Data, IEEE Eng. Med. & Biology, vol. 12, No. 1, pp. 111-119 (1993).

[Bar94a] W. Barrett, E. Bess. Interpolation by directed distance morphing. In R. A. Robb, editor, Visualization in Biomedical Computing 1994, Proc. SPIE 2359, pages 110-121, Rochester, MN, 1994.

[Bar94b] E. Bardinet, L. D. Cohen, N. Ayache. Fitting of iso-surfaces using superquadrics and free-form deformations. In IEEE Workshop on Biomedical Images Analysis (WBIA'94), Seattle, USA, Jun. 1994.

[Bau96] R. Baumann and D. Agluser, Force Feedback for VR based Minimally Invasive Surgery Simulator, Medicine Meets Virtual Reality, San Diego, CA, USA, January (1996).

[Bes92] P. J. Besl, McKay N. D. A method for registration of 3D shapes. IEEE Transactions on PAMI, 14:239-256, Feb. 1992.

[Ben95] S. Benayoun, C. Nastar, N. Ayache. Dense non-rigid motion estimation in sequences of 3d images using differential constraints. In N. Ayache, editor, First international conference on computer vision, virtual reality and robotics in medicine, CVRMed'95, Nice, France, 1995. Springer-Verlag. Lecture Notes in Computer Science.

[Bet95] F. Betting, J. Feldmar, N. Ayache, F. Devernay. a new framework to fuse stereo images with volumetric medical images. In N. Ayache, editor, First International conference on computer vision, virtual reality and robotics in medicine, CVRMed'95, Nice, France, 1995. Springer-Verlag. Lecture Notes in Computer Science.

[Bie98]D. Bielser, V. A. Mainwald, M. H. Gross Interactive Cuts through 3 Dimensional Soft Tissue. Technical Report No 309, Computer Science Department, ETH Zürich, 1998.

[Bil95] J. Bill, J. Reuther, W. Dittmann, et al., Stereolithography in oral and maxillofacial operation planning, In. J. Oral Maxillofac. Surg., Vol. 24, pp. 98-101 (1995).

[Bis96] B. Biswal, E. DeYoe and J. Hyde, Reduction of physiological fluctuations in fMRI using digital filters, Magnetic Resonance in Medicine, Vol. 35, pp. 107-113 (1996)

[Bro95] M. Bro-Nielsen. Modeling elasticity in solids using active cubes application to simulated operations. In N. Ayache, editor, First international conference on computer vision, virtual reality and robotics in medicine, CVRMed'95, Nice, France, 1995. Springer-Verlag. Lecture Notes in Computer Science.

[Bru93] M. E. Brunimer, R. M. Mersereau, R. L. Eisner, R. R. J. Lewine. Automatic detection of brain contours in MRI data sets. IEEE Trans. Med. Imaging, 12:153-166, 1993.

[Buc84] B. Buchanan and E. Shorliffe, Rule-Based Expert Systems, Addison-Wesley, Reading, MA, USA (1984).

[Cai99] K. Caidahl, E. Kazzam, J. Lingber, et al., New Concept in Echocardiography: Harmonic Imaging of Tissue Without Use of Contrast Agent, in The Lancet, Vol. 352, pp. 1264-1270 (1999).

[Can85] J. Canny. A computational approach to edge detection. IEEE Trans. Pattern Anal. Machine Intel., PAMI-8(6):679-698, 1985.

[Car76] M. P. do Carmo. Differential Geometry of Curves and Surfaces. Prentice-Hall, Englewood Cliffs, 1976.

[Cha85] E. Charniak and D. McDermott, Introduction to Artificial Intelligence, Addison-Wesly, Reading, MA, USA (1985).

[Che85] L. S. Chen, Gabor T. Herman, R. A. Reynolds, Jayaram K. Udupa. Surface shading in the cuberille environment. IEEE Comput. Graphics Appl., 5(12):33-43, 1985.

[Che91] C. T. Chen, C. K. Taso, and W. C. Lin. Medical image segmentation by a constraint satisfaction neural networks. IEEE Trans. Nucl. Sci., vol. 38, pp. 678-686, 1991.

[Che98] E. Chen and B. Marcus, Force Feedback for Surgical Simulation, Proc. IEEE, Vol. 86, No. 3, March (1998).

[Cla97] P. Clarysse, D. Friboulet, I. E. Magnin. Tracking geometrical descriptors on 3d deformable surfaces. application to the left-ventricular surface of the heart. IEEE Trans. Med. Imaging, 16(4):392-404, 1997.

[Cha98] F. Chassat and S. Lavallée, Experimental Protocol of Accuracy Evaluation of 6D Localizers for Computer-Integrated Surgery: Application for Four Optical Localizers, Medical Image Computing and Computer-Assisted Intervention (MICCAI) 98; pages 277-284; Cambridge, MA, Springer Lecture Notes in Computer Science 1496 (1998).

[Coh93] L. D. Cohen, I. Cohen. Finite element methods for active contour models and balloons for

2-D and 3-D images. IEEE Transactions on Pattern Analysis and Machine Intelligence, 15(11), Nov. 1993.

[Cot96] S. Cotin, H. Delingette and N. Ayache, Real-time volumetric deformable models for surgery simulation, in Proc. Int. Conf. on Visualization in Biomedical Computing (VBC'96), pp. 535-540 (1996).

[Cot99a] S. Cotin and H. Delingette and N. Ayache, Real-time elastic deformations of soft tissues for surgery simulation, IEEE Transactions On Visualization and Computer Graphics. pg 62-73. 1999,

[Cot99b] S. Cotin and H. Delingette and N. Ayache, A Hybrid Elastic Model allowing Real-Time Cutting, Deformations and Force-Feedback for Surgery Training and Simulation, The Visual Computer 1999 {to appear}

[Cov91] T. Cover and J. Thomas, elements of information Theory, John Wiley & Sons (1991).

[Cox73] H. Coxeter, Regular Polytopes, Dover Publications, New York, NY (1973).

[Cse99] B. Csebfalvi, Fast Volume Rotation using Binary Shear-Warp Factorization, In E. Groeller, H. Loeffelmann, B. Ribarsky (eds.), Data Visualization'99, Springer Wien. (also available as Technical Report TR-186-2-99-07 Abstract, Full Paper.

[Cub4ONL] On-line information is available http://www.cs.sunysb.ed/~vislab/projects/cube/cube.html

[Cut91] C. Cutting. Applications of computer graphics to the evaluation and treatment of major craniofacial malformations. In J. Udupa, G. Herman, editors, 3D imaging in medicine, chapter 6, pages 163-189. CRC-Press, 1991.

[Cze98] R. Czewinski, Line and boundary detection in speckle images, IEEE Tran. Image Processing, Vol. 7, No. 12, pp. 1700-1714 (1998).

[Dav90] D. J. David, D. C. Hemmy, R. D. Cooter. Craniofacial Deformities: Atlas of Three-Dimensional Reconstruction from Computed Tomography. Springer-Verlag, New York, 1990.

[Daw98] S. Dawson and A. Kaufman, "The Imperative for Medical Simulation," Proc. IEEE, vol. 86, No. 3 (1998).

[deB96a] L. de Braal, N. Ezquerra, E. Schwarts, C. Cooke, and E. Garcia, Analyzing and predicting images through a neural network approach, Proc. Visualization in Biomedical Computing (VBC96), pp. 253-259; Hamburg, Germany (1996).

[DeB96b] L. de Braal, N. Ezquerra, C. Cooke, et al., PERFUSE: An Interactive Knowledge-Based System for the Interpretation and Explanation of Cardiac Imagery, Proc. Int. IEEE Conf. of the Engineering in Med. and Biology Soc. (EMBS'96), Amsterdam, The Netherlands; ISBN 90-9010005-9 (1996).

[Dec95]] J. Declerck, G. Subsol, J. P. Thirion, N. Ayache. Automatic retrieval of anatomical structures in 3d medical images. In N. Ayache, editor, First international conference on computer vision, virtual reality and robotics in medicine, CVRMed'95, Nice, France, 1995. Springer-Verlag. Lecture Notes in Computer Science.

[Del34] B. Delaunay, Sur la sphere vide, Izvestia Akademii Nauk SSSR, Otdelenie Matematicheskii i Estestvennyka Nauk, Vol. 7, pp. 793-800; in French (1934).

[Del92] H. Delingette, M. Hebert, K. Ikeuchi. Shape representation and image segmentation using deformable surfaces. Image and Vision Computing, 10(3):132-144, Apr. 1992.

[Del95] C. Delfinado and H. Edelsbrunner, An incremental algorithm for Betti numbers of simplicial complexes on the 3-sphere, Comput. Aided. Geom. Design; Vol. 12; pp. 771-784 (1995).

[Del98] H. Delingette, Towards Realistic Soft Tissue Modeling in Medical Simulation, Proceedings of the IEEE : Special Issue on Surgery Simulation. pp 512-523. Apr 1998.

[Dem97] A. M. Demiris, A. Mayer, H. P. Meinzer, 3-D Visualization in Medicine: An Overview In Roux C et al. Contemporary Perspectives in Three-Dimensional Biomedical Imaging Vol. 30, pp. 79-105, IOS Press: Amsterdam 1997.

[Den95] T. Denney, J. L. Prince, Reconstruction of 3D Left Ventricular Motion from Planar Tagged Cardiac MR Images: an Estimation Theoretic Approach. IEEE Transactions on Medical Imaging, Vol 14, No. 4, December 1995.

[Der87] R. Deriche. Using canny's criteria to derive a recursively implemented optimal edge detector. International Journal of Computer Vision, 1(2), May 1987.

[DeP89] E. DePuey, E. Garcia and N. Ezquerra, 3D Techniques and Artificial Intelligence in Cardiac Imaging, Am. Journal of Roentgenology, Vol. 152, pp. 1161-1168, June (1989).

[Des95] V. Dessenne, S. Lavallée, R. Juiliard, R. Orti, S. Martelli, and P. Cinquin. Computer-assisted knee anterior cruciate ligament reconstruction: First clinical tests. J. Image Guided Surgery, vol. 1, PP. 59-64, 1995.

[DeS99] R. Jets De Simone, G. Glombitza, C. F. Vahl, J. Albers, H. P. Meinzer, S. Hagl, Three-Dimensional Color Doppler: A New Approach for Quantitative Assessment of Mitral Regurgitant, Journal of the American Society of Echocardiography 12 (3), 173-185 (1999).

[Dha90a] A. P. Dhawan and S. Mirsa. Knowledge-based analysis and recognition of 3-D images of the human chest cavity. in Proceedings on Visualization in Biomedical Computing. New York: IEEE Press, 1990.

[DHA90B] A. P. Dhawan and S. Juvvadi. Knowledge-based analysis and understanding of medical images. Comput. Methods Programs Biomed., vol. 33, pp. 221-239. 1990.

[Dia79] G. Diamond and J. Forrester, Likelihood after an electrocardiographic stress test according to age, sex, symptom and depression of S-T segment, New Eng. J. Med., Vol. 300, pp. 1350-1358 (1979).

[DiG94] A. M. DiGioia, B. Jaramaz, R. V. O'Toole. An Integrated Approach to Medical Robotics and Computer Assisted Surgery in Orthopedics. Proc. 1st Int. Symp. Med. Robotics and Computer-Assisted Surgery (MRCAS'94), Pittsburgh, PA, 1994, PP. 106-111.

[DiG98] A. DiGioia, B. Jaramaz, and B. Colgan, Computer assisted orthopedic surgery. Image guided and robotic assistive technologies, Clin. Orthop., Vol. 354, pp. 8-16, Sep. (1998).

[Dod92] J. Doge, B. Brown, E. Bolson and H. Doge, Lumen diameter of normal human coronary arteries, Circulation, vol. 86, No. 1, pp. 232-246 (1992).

[Don94] D. Donoho and I. Johnstone, Threshold selection for wavelet shrinkage of noisy data, Proc. 16th. Annual Int. Conf. IEEE Engineering in Med. and Biology Society (1994).

[Dre88] R. A. Drebin, L. Carpenter, P. Hanrahan, Volume rendering, in Proc. SIGGRAPH'88, J. Dill, Ed., Atlanta, GA, Aug. 1988, vol. 22, pages 65-74.

[Dre89] R. A. Drebin, D. Magid, D. D. Robertson, E. K. Fishman. Fidelity of Three-dimensional CT imaging for detecting fracture gaps. J. Comput. Assist. Tomogr., 13(3):487-489, 1989.

[Dud75] J. Duda and P. Hart, Pattern Analysis and Machine Intelligence, John Wiley & Sons (1975).

[Dui99] P. Duijves, N. Ezquerra and F. Post, A Floating-Volume Method for Skeleton Extraction from Angiographic X-ray Images, Delft University of Technology, Technical Report, April (1999).

[Dun91] J. S. Duncan, R. L. Owen, L. H. Staib, P. Anandan. Measurement of non-rigid motion using contour shape descriptors. In Proc. Computer Vision and Pattern Recognition, pages 318-324, Lahaina, Maui, Hawaii, Jun. 1991.

[Dun95] J. Duncan, A Unified framework to assess myocardial function from 4D images, Lecture Notes in Computer Science: First Int. Conf. on Computer Vision, Virtual Reality, and Robotics in Medicine, pp. 327-337 (1995).

[Ear92] R. Earnshaw and N. Wiseman, eds.; An Introduction to Scientific Visualization, Springer, Berlin, Germany (1992).

[Ear93] R. Earnshaw and D. Watson, eds.; Animation and Scientific Visualization, Academic Press, New York, USA (1992).

[Ede94] H. Edelsbrunner and E. MŸcke, Three-Dimensional Alpha Shapes, ACM Trans. on Graphics; Vol. 13, No. 1, pp. 43-72 (1994).

[Edm97] C. V. Edmond, D. Heskamp, D. Sluis, D. Stredney, G. J. Wiet, D. J. Sessana, R. Yagel, S. J. Weghorst, P. Oppenheimer, J. Miller, M. Levin, L. Rosenberg, Simulation for ENT endoscopic surgical training, in Proceedings of Medicine Meets Virtual Reality 5, K. S. Morgan, H. M. Hoffman, D. Stredney, S. J. Weghorst, Eds. San Diego, CA: IOS Press, 1997, pages 518-528.

[Edm98] C. V. Edmond, G. J. Wiet, B. Bolger. Surgical Simulation in Otology. Otolaryng Clin of NA 31:p 369-81, 1998.

[Eka98] D. Edatodramis, G. Sz? leky and G. Gerig, Detecting and Inferring Brain Activation from functional MRI by Hypothesis-Testing Based on the Likelihood Ratio, Medical Image Computing and Computer-Assisted Intervention (MICCAI) 98;

pages 578-589; Cambridge, MA, Springer Lecture Notes in Computer Science 1496 (1998).

[Ell96] R. Ellis, O. Ismael and M. Lipsett, Design and evaluation of high-performance haptic interface, Robotica, Vol. 4, pp. 321-327 (1996).

[Els93] P. A. van den Elsen, E. J. D. Pol, M. A. Viergever. Medical image matching: A review with classification. IEEE Eng. Med. Biol. Magazine, 12(1):26-39, 1993.

[Eng97a] U. Engelmann. A. Schröter, U. Baur, O. Werner, B. Güransson, E. Borälv, M. Schwab, H. Müller, M. Bahner, H. P. Meinzer. Experiences with the German teleradiology system MEDICUS. Computer Methods and Programs in Biomedicine 54 (1997) 131-139.

[Eng97b] U. Engelmann. A. Schröter, U. Baur, O. Werner, M. Schwab, H. Müller, M. Bahner, H. P. Meinzer. Second Generation Teleradiology. In: Lemke HU, Vannier MW, Inamura K (eds): Computer Assisted Radiology and Surgery. Amsterdam: Elsevier (1997) 632-637.

[Eng98a] U. Engelman, M.L. Bahner. Teleradiology: Improving Communication in Radiological Diagnostics. In Deutsches Krobsforschungszentrum Current Cancer Research 1998. New York. Springer (1998) 134-139.

[Eng98b] U. Engelmann, A. Schröter, H. Evers, M. Schwab, U. Baur, H. P. Meinzer. Teleradiology: Not always Plug & Play. A Case Report. In Piqueras J, Carreno JC (eds). Proceedings of the 16th EuroPACS Annual Meeting. Barcelona: Vall d'Hebron (1998) 159-162.

[Eng98c] U. Engelmann. A. Schröter, U. Baur, O. Werner, M. Schwab, H. Müller, H. P. Meinzer. The Evolution of a German Teleradiology System. In Cesnik B, McCray AT, Scherrer JR (eds). MedInfo'98; 9th World Congress on Medical Informatics. Amsterdam: IOS Press (1998) 255-259.

[Eng98d] U. Engelmann, A. Schröter, U. Baur, M. Schwab, O. Werner, M. H. Makabe, H. P. Meinzer. Openness in (Tele-) Radiology Workstations: The CHILI PlugIn Concept. In: Lemke HU, Vannier MW, Inamura K, Farman A (Eds). CAR'98 - Computer Assisted Radiology and Surgery. Amsterdam: Elsevier (1998) 437-442.

[Ess93] I. Essa, S. Sclaroff and A. Pentland, Physically-based modeling for graphics and vision, in Directions in Geometric Computing, R. Martin, ed.; pp. 160-196; Information Geometers, U.K. (1993).

[Eve99] H. Evers, A. Mayer A, U. Engelmann, A. Schröter, U. Baur, K. Wolsiffer, H. P. Meinzer. Extending a teleradiology system by tools for visualization and volumetric analysis through a plug-in mechanism. Int. Journal of Medical Informatics 53, 2-3 (1999) 265-275.

[Ezq86] N. Ezquerra, E. Garcia, E. De Puey and W. Robbins, Development of an Expert System for Interpreting Medical Images, Proc. IEEE Int. Conf. Systems, Man and Cybernetics, Vol. 1, pp. 205-210, October (1986).

[Ezq92] N. Ezquerra, A. Pazos, F. Martin and V. Maojo, A Neural Networks Approach to Medical Image Interpretation, Proc. World Congress on Medical Informatics (MEDINFO'92), Geneva, Switzerland (1992).

[Ezq96a] N. Ezquerra and R. Mullick, Model-Guided Segmentation of 3D Imagery, CVGIP: Graphical Models and Image Processing, Vol. 58, No. 5, pp. 510-523, November (1996).

[Ezq96b] N. Ezquerra and R. Mullick, Topological goniometry: An Approach to 3D Pose Determination, ACM Trans. on Graphics; Vol. 15, No. 2, pp. 99-120, April (1996).

[Ezq98] N. Ezquerra, S. Capell, L. Klein and P. Duijves, Model-Guided Labeling of Coronary Structure, IEEE Trans. Medical Imaging, Vol. 17, No. 3, pp. 429-441 (1998).

[Ezq99] N. Ezquerra, L. de Braal, E. Garcia, et al., Interactive, Knowledge-Guided visualization of 3D medical imagery Future Generation Computer Systems (FGCS); L. Hertzberger and P. Sloot, eds.; Vol. 15, pp. 59-73, Elsevier Publishers (1999).

[Fab95] T. Faber, D. Cooke, J. Peifer, et al., Three-dimensional displays of left ventricular epicardial surface from standard cardiac SPECT perfusion quantification techniques, J. Nuc. Med., Vol. 36, No. 4, pp. 697-703 (1995).

[Fab99] T. Faber, D. Cooke, R. Folks, et al., Left Ventricular Function and Perfusion from Gated SPECT Perfusion Images: An Integrated Method, J. Nuc. Med., Vol. 40, No. 4, pp. 650-659 (1999).

[Fan96] J. Fan and A. Laine, Multiscale constrast enhancement and denoising in digital radiographs, in Wavelets in Medicine and Biology, A. A. a. M. Unser, ed.; CRC Press, pp. 163-189 (1996).

[Far90] G. Farin, Curves and Surfaces for Computer Aided Geometric Design: A Practical Guide, Academic Press, 2nd. ed. (1990)

[Fen98] R. A. Drebin, D. Magid, D. D. Robertson, E. K. Fishman. Fidelity of Three-dimensional CT imaging for detecting fracture gaps. J. Comput. Assist. Tomogr., 13(3):487-489, 1989.

[Fin95] P. A. Finlay, M. H. Ornstein. Controlling the Movement of a Surgical Laparoscope. IEEE Eng. Med. Biol. Mag., vol. 14, pp. 289-291, 1995.

[Fol90] J. D. Foley, A. van Dam, S. K. Feiner, J. F. Hughes. Computer Graphics: Principles and Practice. Addison-Wesley Publ. Comp., Reading, MA, 2. edition, 1990.

[For98a] M. Fornefett, K. Rohr, R. Sprengel, H. S. Stiehl, Incorporating Orientation Attributes in Landmark-based Elastic Medical Image Registration, Proc. Image and Multidimensional Digital Signal Processing (IMDSP’98), July 12-16, 1998, Alpbach/Austria, H. Niemann, H. P. Seidel, B. Girod (Eds.), infix Verlag Sankt Aug. 1998, 37-40.

[For98b] M. Fornefett, K. Rohr, R. Sprengel, H. S. Stiehl, Elastic Medical Image Registration using Orientation Attributes at Landmarks, Proc. Medical Image Understanding and Analysis (MIUA’98), Univ. of Leeds/UK, 6-7 July 1998, E. Berry, D. C. Hogg, K. V. Mardia, M. A. Smith (Eds.), University Print Services Leeds 1998, 49-52.

[Fra98a] R. P. Frankenthaler, V. Moharir, R. Kikinis, P. van Kipshagen, F. Jolesz, C. Umans, M. P. Fried. Virtual otoscopy. Otolaryngol Clin North Am 1998 Apr 31:2 383-92.

[Fra98b] A. Frangi, W. Niessen, K. Wincken, and M. Viergever, Multiscale Vessel Enhancement Filtering, Proc. 1998 Medical Image Computing and Computer-Aided Intervention (MICCAI’98), Springer Lecture Notes in Computer Science 1496, pp. 130-137 (1998).

[Fri92] D. Friboulet, I. Magnin, A. Pommert, M. Amiel. 3D curvature features of the left ventricle from CT volumic images. In SPIE, Mathematical Methods in Medical Imaging, volume 1768, pages 182-192, Jul. 1992. San Diego.

[Fuc89] R. Fuchs, J. Poulton, J. Eyles, T. Greer, J. Goldfeather, D. Ellsworth, S. Molnar, G. Turk, B. Tebbs, L. Israel, Pixel-planes 5: A heterogeneous multiprocessor graphics system using processor-enhanced memories, in Proc. SIGGRAPH'89, Boston, MA, pages 79-88.

[Gar96] E. Garcia, C. Cooke, E. Krawczynska, et al., Expert System Interpretation of Myocardial Perfusion Tomograms: Enhancements and Validation, Circulation, vol. 92, No. 8, Number 0048 (1996).

[Gar99] E. Garcia, R. Folks, C. Santana, E. Krawczynska, N. Ezquerra, et al., Expert System Interpretation of Myocardial Perfusion Tomograms: Validation Using 655 Prospective Patients, J. Nuc. Med., Vol. 40, No. 5, 126P (1999).

[Gau93] J. Gauch, S. Pizer. Multiresolution analysis of ridges and valleys in grey scale images. IEEE Transactions on Pattern Analysis and Machine Intelligence, 15(6):635-646, 1993

[Gei92] B. Geiger. 3D simulation of delivery for cephalopelvic disproportion. In First int. works. on mechatronics in medicine and surgery, Oct. 1992. Costa del Sol, Spain.

[Gei95] B. Geiger, R. Kikinis. Simulation of endoscopy. In Nicholas Ayache, editor, Computer Vision, Virtual Reality and Robotics in Medicine, Proc. CVRMed'95, volume 905 of Lecture Notes in Computer Science, pages 277-281. Springer-Verlag, Berlin, 1995.

[Ger92] G. Gerig, 0. Kübler, R. Kikinis, F. A. Jolesz. Nonlinear anisotropic filtering of MRI data. IEEE Trans. Med. Imaging, 11(2):221-232, 1992.

[Gia99] A. Giachetti, On-line analysis of echocardiographic image sequences, in Medical Image Analysis, vol. 2, No. 3, pp. 261-284 (1999).

[Gib97] S. Gibson, J. Samosky, A. Mor, C. Fyock, E. Grimson, T. Kanade, R. Kikinis, H. Lauer, N. McKenzie, S. Nakajima, U. Ohkami, R. Osborne, and A. Sawada. Simulating arthroscopic knee surgery using volumetric object representations, real-time volume rendering and haptic feedback. in Proc. CVRMed-MRCAS'97, Grenoble, France, 1997, pp. 369-378.

[Gio95] C. Giorgi, H. Eisenherg, G. Costi, E. Gallo, G. Garibotto, D. S. Casolino. Robot-Assisted Microscope for Neurosurgery. J. Image Guided Surgery, vol. 1, pp. 158-163, 1995.

[Gla95] D. Glauser, U. Fankhauser, M. Epitaux, J.-L. Hefti, A. Jaccottet. NeuroSurgical Robot Minerva: First Results and Clinical Developments. J. Imago Guided Surgery, vol. 1, pp. 266-272, 1995.

[Glo98a] G. Glombitza, R. DeSimone, M. Merdes, A. Mayer, C. F. Vahl, S. Hagl, H. P. Meinzer, Three-dimensional visualization and volumetric assessment of valvular regurgitation jets in echocardiography. In: Lemke HU, Vannier MW, Inamura K, Farman A (Eds). CAR'98 - Computer Assisted Radiology and Surgery. Amsterdam: Elsevier (1998) 170-175.

[Glo98b] G. Glombitza, C. Herfarth, W. Lamade, H. P. Meinzer, Virtual Operation planning in Liver Surgery. In Deutsches Krebsforschungszentrum - Current Cancer Research 1998. New York: Springer (1998) 99-104.

[Glo99a] G. Glombitza, R. De Simone, M. Merdes M, A. Mayer, C. F. Vahl, S. Hagl, Three-dimensional visualization and volumetric assessment of valvular regurgitant jets in echocardiography, Proceedings . Computer Assisted Radiology and Surgery 1998. (eds. H. U. Lemke, M. W. Vannier, K. Inamura, A. G. Farman), 170-175 (1999).

[Glo99b] G. Glombitza, W. Lamade, A. M. Demirirs, M. R. Göpfert, A. Mayer, M. L. Bahner, H. P. Meinzer, G. Richter, T. H. Lehnert, C. H. Herfarth, Virtual planning of liver resections: image processing, visualization and volumetric evaluation, International Journal of Medical Informatics 53 (2, 3), 225 - 237. 1999.

[Gon91] I. Gong, C. Kulikowski and R. Mezrich, Valley-enhanced histogram computation for MR image segmentation, presented at the Annual Meeting of the Am. Soc. of Neuroradiology, Mar. (1991).

[Gre94] W. Greenleaf and M. Tovar, Augmenting Reality in Rehabilitation Medicine, in Artificial Intelligence in Medicine, Vol. 6, 289-299 (1994).

[Gre95] P. S. Green, J. W. Hill, J. F. Jensen, A. Shah. Telepresence Surgery. IEEE Eng. Med. Biol. Mag., vol. 14, pp. 324-329, 1995.

[Gri89]] J. Grimes, L. Kohn, R. Bharadhwaj, The Intel i860 64-bit processor: A general purpose CPU with 3D graphics capabilities, IEEE Comput. Graphics Appl., vol. 9, no. 4, pages 85-94, Jul. 1989.

[Gri94] W. E. L. Grimson, T. Lozano-Perez, W. M. Wells, III, G. J. Ettinger, S. J. White, and R. Kikinis, An automated registration method for frameless stereotaxis, image guided surgery, and enhanced reality visualization. Proc. IEEE Computer Visualization and Pattern Recognition, 1994, pp. 430-436

[Gri95] W. E. L. Grimson, G. J. Ettinger, S. J. White, P. L. Gleason, T. Lozano-Perez, W. M. Wells III, R. Kikinis. Evaluating and validating an automated registration system for enhanced reality visualization in surgery. In N. Ayache, editor, First International conference on computer vision, virtual reality and robotics in medicine, CVRMed'95, Nice, France, 1995. Springer-Verlag. Lecture Notes in Computer Science.

[Gri96] E. Grimson, et al., An Automatic Registration Model for Frameless Stereotaxy, Image-Guided Surgery and Enhanced Reality Visualization, IEEE Trans. Med. Img., Vol. 15, No. 2, pp. 129-140, April (1996).

[Gri98] E. Grimson, M. Leventon, G. Ettinger, et al., Clinical Experience with a High Precision Image-Guided Neurosurgery System, Proc. 1998 Medical Image Computing and Computer-Aided Intervention (MICCAI'98), Springer Lecture Notes in Computer Science 1496, pp. 63-73 (1998).

[Gro98] M. Gross, Computer Graphics in Medicine: from Visualization to Surgery Simulation, Computer Graphics, February (1998).

[Gue93] A. Guéziec. Large deformable splines, crest lines and matching. In Int. Conf. on Computer Vision, ICCV'93, Berlin, Germany, 1993.

[Gut91] B. Guthrie and J. R. Adler. Frameless stereotaxy: Computer interactive neurosurgery. Persp. Neurolog. Surgery, vol. 2, no.1, pp 1-22, 1991.

[Hab98] E. Haber, D. Metaxas and L. Axel, Motion Analysis of the Right Ventricle from MRI Images, Proc. 1998 Medical Image Computing and Computer-Aided Intervention (MICCAI'98), Springer Lecture Notes in Computer Science 1496, pp. 177-188 (1998).

[Had98] S. Hadley, S. Johnsons and C. Pelizzari, Calibration of Video Cameras to the Coordinate System of a Radiation Therapy Treatment Machine, Medical Image Computing and Computer-Assisted Intervention (MICCAI) 98; pages 223-231; Cambridge, MA, Springer Lecture Notes in Computer Science 1496 (1998).

[Hag99] A. Hagemann, K. Rohr, H. S. Stiehl, Nonrigid Matching of Tomographic Images Based on a Biomechanical Model of the Human Head, Medical Imaging 1999 - Image Processing (MI'99), Proc. SPIE. Symposium, Feb. 20-26, 1999, San Diego/CA

[Har78] R. A. Harris, D. Lowell, et. al., Non-invasive numerical dissection and display of anatomic structure using computerized X-ray tomography, in Proc. SPIE, vol. 152, 1978, pages 10-18.

[Har92] R. Haralick and L. Shapiro, Computer and Robot Vision., Vols. I and II, Addison Wesley, Reading, MA, USA (1992).

[Har93] S. Haring, M. A. Viergever, J. N. Kok. A multiscale approach to image segmentation using Kohonen networks. In H. H. Barrett, A. F. Gmitro, editors, Information Processing in Medical Imaging, Proc. IPMI'93, volume 687 of Lecture Notes in Computer Science, pages 212-224. Springer-Verlag, Berlin, 1993.

[Har99] T. Hartkens, K. Rohr, H. S. Stiehl, Performance of 3D differential operators for the detection of anatomical point landmarks in MR and CT images, Medical Imaging 1999 - Image Processing (MI'99), Proc. SPIE. Symposium, Feb. 20-26, 1999, San Diego/CA.

[Hen79] M. Henle, A Combinatorial Introduction to Topology, W. Freeman and Co., San Francisco, CA (1979).

[Her92b] G. Herman, Discrete Multidimensional Jordan Surfaces, CVGIP: Graphical Modeling and Image Proc., Vol. 54, pp. 507-515 (1992).

[Her93] G. Herman, Oriented surfaces in digital spaces, CVGIP: Graphical Models and Image Proc.; Vol. 55, pp. 381-396 (1993).

[Hem85] D. C. Hemmy, P. L. Tessier. CT of dry skulls with craniofacial deformities: Accuracy of three-dimensional reconstruction. Radiology, 157(1):113-116, 1985.

[Hem92] P. F. Hemler, T. Koumrian, J. R. Adier, and B. Guthrie. A three dimensional guidance system for frameless stereotactic neurosurgery. in Proc. 5th Ann. IREE Symp. Computer-Based Medical Systems, Durham, NC, June 1992, pp. 309-314.

[Him98] J. Himpens, G. Leman, G. B. Cardiere. Telesurgical Laparoscopic Cholecystectomy. Surg Endosc 12: 1091, 1998.

[Ho95] S. C. Ho, R. D. Hiberd, and B. L. Davies. Robot assisted knee surgery. In IEEE Eng. Med. Biol. Mag., vol. 14, pp. 292-300, 1995

[Hod95a] L. Hodges, B. Rothbaum, R. Cooper, et al., Virtual environments for treating the fear of heights, IEEE Computer Vol. 28, No. 7, pp. 27-34 (1995).

[Hof95] H. Hoffman, A. Irwin, R. Ligon, M. Murray, C. Tohsaku. Virtual Reality - Multimedia Synthesis: Next-generation Learning Environments for Medical Education. Jour Biocommunications Vol 22: No 3, pp 2-7, 1995.

[Hof97] H. Hoffman, D. Vu. Virtual reality: teaching tool of the twenty-first century? Acad. Med. 1997 Dec 72:12 1076-81.

[Hon95] L. Hong, A. Kaufman, Y. Wei, A. Viswambharn, M. Wax, Z. Liang. 3D Virtual Colonoscopy. Proc. 1995 Symposium on Biomedical Visualization, 1995, 26-32.

[Hon97] L. Hong, S. Muraki, A. Kaufman, D. Bartz, T. He. Virtual Voyage: Interactive Navigation in the Human Colon. Proc. SIGGRAPH'97, Aug. 1997, 27-34

[Hoo98] R. M. Hoogeveen, C. Bakker, and M. Viergever, Limits to the accuracy of vessel diameter measurement in MR angiography, Journal of Magnetic Resonance Imaging, Vol. 8, pp. 1228-1237 (1998).

[Höhne86] K. H. Höhne, R. Bernstein. Shading 3D-images from CT using gray level gradients, IEEE Trans. Med. Imaging, MI-5(1):45-47, 1986.

[Höh87] K. H. Höhne, R. L. Delapaz, R. B. Stein, R. C. Taylor, Combined surface display and reformatting for the three-dimensional analysis of tomographic data, in Investigative Radiology, vol. 27, no. 7, pages 658-664, Jul. 1987.

[Höh90a] K. Höhne, H. Fuchs, S. Pizer, editors. 3D imaging in medicine. Springer-Verlag, 1990. NATO ASI Series, vol. F60.

[Höh92a] K. H. Höhne, M. Bomans, B. Pflesser, A., Pommert, M. Riemer, T. Schiemann, U. Tiede. Anatomic realism comes to diagnostic imaging. Diagn. Imaging, (1): 115-121, 1992.

[Höh92b] K. H. Höhne, W. A. Hanson. Interactive 3D-segmentation of MRI and CT volumes using morphological operations. J. Comput. Assist. Tomogr, 16(2):285-294, 1992.

[Höh92c] K. Höhne, A. Pommert, M Riemer, T. Schiemann, R. Schubert, U. Tiede. Framework for the generation of 3D anatomical atlases. In R. Robb, editor, Visualization in Biomedical Computing, volume 1808, pages 510-520. SPIE, 1992. Chapel Hill.

[Höh95] K. H. Höhne, B. Pflesser, A. Pommert, M. Riemer T. Schiemann, R. Schubert, U. Tiede. A new representation of knowledge concerning human anatomy and function. Nature Med., 1(6):506-511, 1995.

[Hyc92] M. E. Hyche, N. Ezquerra and R. Mullick, Spatiotemporal Detection of arterial Structure Using Active Contours, Proc. Visualization in Biomedical Computing (VBC 92), SPIE Vol. 1808, pp. 52-62; Chapel Hill, NC, USA (1992).

[Hun95] W. Hunter, L. A. Jones, M. A. Sagar, S. R. Lafontaine, P. J. Hunter. Ophthalmic microsurgical robot and associated virtual environment.
Comput. Biol.. Med., vol. 25, no. 2, pp. 173-182,1995

[Jac99] G. Jacob, A. Noble, M. Mulet-Parada and A. Blake, Evaluating a robust contour tracker on echocardiographic sequences, Medical Image Analysis, vol. 3, No. 1, pp. 63-75 (1999).

[Jai89] A. Jain, Fundamentals of Digital Image Processing, Prentice Hall, Englewood Cliffs, NH (1989).

[Joh97ONL] C. Johnson,
Computational Steering; available on-line at: www.cs.utah.edu/~sci/projects/sci_comp.html

[Jon96] S. Jones, R. M. Satava, Virtual endoscopy of the head and neck, in Proc. MMVR'96, San Diego, CA, pages 152-156.

[Jos98]] L. Joskowicz, L. Tockus, Z. Yaniv, A. Simkin, C. Milgrom. Computer-Aided Image-Guided Bone Fracture Surgery - Concept and Implementation, Proc. 12th Int. Symp. on Computer Assisted Radiology and Surgery, H. U. Lemke et. al. eds, 1998.

[Jos99] L. Joskowicz, C. Milgrom, A. Simkin, L. Tockus, Z. Yaniv. FRACAS: A System for Computer-Aided Image-Guided Long Bone Fracture Surgery, Journal of Computer-Aided Surgery, Vol. 3(6), May 1999.

[Kal91] A. Kalvin, C. Cutting, B. Hadd and M. Noz, Constructing topologically connected surfaces for the comprehensive analysis of 3d medical structures, SPIE Image Proc. vol. 1445, pp. 247-258 (1991).

[Kal92] A. Kalvin, D. Dean, J. Hublin, M. Braun. Visualization in anthropology: reconstruction of human fossils from multiple pieces. In A. Kaufman, G. Nielson, editors, Proc. of the IEEE VISUALIZATION’92, pages 404-410. 1992.

[Kal93] R. Kalawsky, The Science of Virtual Reality and Virtual Environments, Addison Wesley (1993).

[Kas87a] M. Kass, A. Witkin and D. Terzopoulos, Snakes: Active Contour Models, IEEE First International Conference on Computer Vision, pp. 259-268 (1987).

[Kas87b] M. Kass, Z. Witkin, D. Terzopoulos. Snakes: Active contour models. International Journal of Computer Vision, 1:321-331, 1987.

[Kaz95] P. Kazanzides, B. D. Mittelstadt, B. L. Musits, W. L. Bargar, J.F. Zuhars, B. Williamson, P. W. Cain and E. J. Carbone. An integrated
system for cementless hip replacement. In IEEE Eng. Med. Biol. Mag., vol. 14, pp. 307-313, 1995.

[Kau91] A. Kaufman, ed.; Volume Visualization, IEEE Comp. Soc. Press, Los Alamitos, CA, USA (1991).

Kau93 A. Kaufman, D. Cohen, and R. Yagel, Volume Graphics, IEEE Computer, pp. 51-64 (1993).

[Kau94] A. Kaufman, K. H. Höhne, W. Krüger, L. J. Rosenblum, P. Schroder. Research issues in volume visualization. IEEE Comput. Graphics Appl., 14(2):63-67, 1994.

[Kee96] E. Keeve, S. Girod and B. Girod, Computer-Aided Craniofacial Surgical Planning and Evaluation, in Computer-Assisted Radiology, H. Lemke et al., eds.; pp. 757-763; Elsevier Science B. V., The Netherlands 91996).

[Kel93] P. Keller and M. Keller, Visual Cues: Practical Data Visualization, IEEE CS Press, Los Alamitos, CA, USA (1993).

[Ken92] J. Kent, W. Carlson and R. Parent, Shape transformation for polyhedral objects, Computer Graphics, Vol. 26, pp. 47-54 (1992).

[Ken96] Y. Kenmochi, N. Ezquerra and A. Imiya, Polyhedra Generation from Lattice Points, Proc. 6th. Int. Conf. on Discrete Geometry for Computer Imagery (DCI’96); Lyon, France, December (1996).

[Kes94] M. L. Kessler, D. L. McShan. An application for design and simulation of conformal radiation therapy. In Richard A. Robb, editor, Visualization in Biomedical Computing 1994, Proc. SPIE 2359, pages 474-483, Rochester, MN, 1994.

[Kie95] T. C. Kienzle, S. D. Stulherg, M. Peshkin, A. Quaid, J. Lea, A. Goswami, C. Wu. Total Knee Replacement. IEEE Eng. Med. Biol Mag., vol. 14, pp. 301-306, 1995.

[Kik95] R. Kikinis, P. L. Gleason and F. A. Jolesz. Surgical planning using computer-assisted three-dimensional reconstruction.
In Computer-Integrated Surgery, R. U. Taylor et al., Eds. Cambridge, MA: MIT Press, 1995, pp. 147-154.

[Kik96] R. Kikinis, M. E. Shenton, D. Y. Iosifescu, R. W. McCarley, P. Saiviroonporn, H. H. Hokama, A. Robatino, D. Metcalf, C. G. Wible, C. M. Portas, R. M. Donnino, F. A. Jolesz. A digital brain atlas for surgical planning, model driven segmentation, and teaching. IEEE Trans. Visualization Comput. Graphics, 2(3):232-241, 1996.

[Kle89] G. Klein, Recognition-primed decisions, in Advances in Man-Machine Systems Research, vol.5, W. Rouse, ed.; pp. 47-92 (1989).

[Kli95] G. Klinker, I. Carlbom, W. Hsu, D. Terzopoulos. Biomedical data exploration meets telecollaboration. Proc. First International Conference on Computer Vision, Virtual Reality, and Robotics in Medicine (CVRMed'95), Nice, France, April, 1995, in Lecture Notes in Computer Science, Vol. 905, Springer-Verlag, Berlin, 1995, 84-91.

[Kob98] E. Kobayashi, K. Masamune, T. Dohi and D. Hashimoto, A New Laparoscope Manipulator with an Optical Zoom, Medical Image Computing and Computer-Assisted Intervention (MICCAI) 98; pages 207-214; Cambridge, MA, Springer Lecture Notes in Computer Science 1496 (1998).

[Koc96] R. M. Koch, M. H. Gross, F. R. Carls, D. F. von Büren, G. Fankhauser, Y. I. H. Parish. Simulating Facial Surgery Using Finite Element Models. Proceedings of SIGGRAPH’96 (New Orleans, Los Angeles, Aug. 4-9, 1996). In Computer Graphics Proceedings, Annual Conference Series, ACM SIGGRAPH, pp. 421-428, 1996

[Koc98] R. M. Koch, M. H. Gross, A. A. Bosshard. Emotion Editing using Finite Elements. Proceedings of the Eurographics’98 (Lisbon, Portugal, Sept. 2-4, 1998), Computer Graphics Forum, Vol. 17, No. 3, C295-C302, 1998

[Koc99] R. M. Koch, S. H. M. Roth, M. H. Gross, A. P. Zimmermann, and H. F. Sailer: A Framework for Facial Surgery Simulation, Technical Report 326, ETH Zürich, Institute of Scientific Computing, June 1999.

[Koe99] A. Koenig, H. Doleisch, E. Groeller, Multiple Views and Magic Mirrors - MRI Visualization of the Human Brain, Proceedings of Spring Conference on Computer Graphics and its Applications 1999 (SCCG'99), Budmerice, Slovakia, April 28th. -May 1st, 1999. (also available as Technical Report TR-186-2-99-08).

[Koh88] T. Kohonen. Self-Organization and Associative Memory. Springer-Verlag, Berlin, 2. edition, 1988.

[Kra98] C. Krapichler, M. Haubner, R. Engelbrecht, K. H. Englmeier. VR interaction techniques for medical imaging applications. Comput Methods Programs Biomed 1998 Apr 56:1 65-74.

[Kru94] W. Krueger, B. Froehlich. The responsive workbench. IEEE Comput. Graphics Appl., 14(3):12-15, 1994.

[Kyr98] S. Kyriacou and C. Davatzikos, A Biomechanical Model of Soft Tissue Deformation, with Applications to Non-rigid Registration of Brain Images with Tumor Pathology, Medical Image Computing and Computer-Assisted Intervention (MICCAI) 98; pages 531-538; Cambridge, MA, Springer Lecture Notes in Computer Science 1496 (1998).

[Lai97] S. Lai and B. Vemuri, Physically-based adaptive preconditioning for early vision, IEEE Trans. Patt. An. & Mach. Intelligence, Vol. 6, No. 6, pp. 594-607 (1997).

[Lam88] Y. Lamdan, H. Wolfson. Geometric hashing: a general and efficient model-based recognition scheme. In Proceedings of the Second International Conference on Computer Vision (ICCV), 1988.

[Lam94] R. Lamson, Virtual Therapy of Anxiety Disorders, CyberEdge J., Vol. 4, No. 2, pp. 6-8 (1994).

[Lau91] D. Laur and P. Hanrahan, Hierarchical splatting: A progressive refinement algorithm for volume rendering, Comput. Graphics, Vol. 25, No. 4, pp. 285-288 (1991).

[Lav91] S. Lavallée, R. Szeliski, L. Brunie. Matching 3D smooth surfaces with their 2d projections using 3D distance maps. In SPIE, Geometric Methods in Computer Vision, Jul. 25-26 1991. San Diego.

[Lav96] S. Lavallée, Registration for Computer-Integrated Surgery: Methodology, State of the Art, in Computer-Integrated Surgery, MIT Press (1996).

[Lee93] N. Lee, T. Poston and A. Rosenfeld, Holes and genus of 2D and 3D digital images, CVGIP: Graphical Models and Image Proc., Vol. 25, No. 1, pp 20-47, January (1993).

[LeG98] M. Leventon and E. Grimson, "Multi-modal Volume Registration Using Joint Intensity Distributions," Medical Image Computing and Computer-Assisted Intervention (MICCAI) 98; pages 1057-1066; Cambridge, MA, Springer Lecture Notes in Computer Science 1496 (1998).

[Leu95] J. Leugyel, D. P. Greenberg, Popp R. Time-Dependent Three-Dimensional Intravascular Ultrasound. In Computer Graphics Proceedings, pages 457-464, Los Angeles, 1995. SIGGRAPH

[Lev88] M. Levoy. Display of Surface from Volume Data. IEEE Computer Graphics and Applications, 8(3):29-37, 1988.

[Lev92] J. Levy-Vehel, P. Mignot, J. P. Berroir. Multifractal, texture and image analysis. In CVPR'92, Urbana Champaign, 1992.

[Lev96] J. Levy, Virtual Reality Hysteroscopy, J. Am. Assoc. Gynecol. Laparoscopy, Vol. 3, No. 4 Supplement, pp. S25-S26, August (1996).

[Lev98] M. Leventon and E. Grimson, Multi-modal Volume Registration Using Joint Intensity Distributions, Medical Image Computing and Computer-Assisted Intervention (MICCAI) 98; pages 1057-1066; Cambridge, MA, Springer Lecture Notes in Computer Science 1496 (1998).

[Lin98a] T. Lindeberg, Edge detection and ridge detection with automatic scale selection, Int. J. Computer Vision, vol. 30, No. 2, pp. 117-154, Nov. (19998).

[Lin98b] T. Lindeberg, Feature detection with automatic scale selection, Int. J. Computer Vision, Vol. 30, No. 2, pp. 79-116, Nov. (1998).

[Liu93] I. Liu and Y. Sun, Recursive tracking of vascular networks in angiograms based on the detection-deletion scheme, IEEE Trans. on Med. Imaging, Vol. 12, No. 2, June (1993).

[Liu98] A. Liu, E. Bullitt, and S. Pizer, "3D/2D Registration via Skeletal Near Projective Invariance in Tubular Objects," Medical Image Computing and Computer-Assisted Intervention (MICCAI) 98; pages 1057-1066; Cambridge, MA, Springer Lecture Notes in Computer Science 1496 (1998).

[Lo94] L-J Lo, J. L. Marsh, M. W. Vannier, V. V. Patel. Craniofacial computer-assisted surgical, planning and simulation. Clin. Plast. Surg., 21(4):501-516, 1994

[Lor87] W. Lorensen and E. Cline, Marching Cubes: A High-resolution 3D surface construction algorithm, ACM SIGGRAPH 87, Vol. 21, pp. 163-169 (1988).

[Lor97] C. Lorenz, I. Carlsen, T. Buzug et al., Multiscale line segmentation with automatic estimation of width, contrast and tangential direction in 2D and 3D medical images, in Proc. CVRMed-MRCAS 97, J. Troccaz, E. Grimson and R. Mosges, eds.; berling; Springer-Verlag Lecture Series in Computer Science, pp. 233-242 (1997).

W. Lorensen.
Marching through the visible man. Online Available: www.crd.ge.com/esl/cgsp/projects/vm/

[Lor95] W. Lorensen, F. Jolesz and R. Kikinis, The exploration of cross-sectional data with a virtual endoscope, in Interactive Technology and the New Paradigm for Healthcare, R. Satava, K. Morgan and H. Sieberg, eds.; Washington, DC, USA; pp. 221-230; IOS Press (1995).

[Ltpn96] J. López, D. Tost, A. Puig, and I. Navazo. Voldmi: An open system for volume modeling and visualization. Computer Graphics, 20(5):703-712, 1996.

[Luc97] M. Lucente, Interactive three-dimensional holographic displays: Seeing the future in depth, Comput. Graphics, Vol. 31, No. 2, pp. 63-67, May (1997).

[Mac94] R. J. Maciunas, R. L. Galloway, and J. W. Latimer. The application accuracy of stereotactic frames. Neurosurgery, vol. 35, no. 4, pp. 6,82--695, 1994.

[Mad93] J. Madrid, R. Mersereau, and N. Ezquerra, Topological considerations on gray level skeletonization, Proc. Conf. on Visual Comm. and Image Processing, SPIE Vol. 1818, pp. 392-401 (1993).

[Mad96] J. Madrid and N. Ezquerra, Automatic 3D Segmentation of MRI Brain Tissue Using Filters by Reconstruction, in Mathematical Morphology and Its Applications to Image and Signal Processing, Proc. 1996 Int. Sympo. on Math. Morphology (ISMM 96), pp. 417-424, P. Maragos, R. Schafer and A. Butt, eds., Kluwer Academic Pub., Boston, MA, USA (1996).

[Mae97] F. Maes, A. Collignon, D. Vadermeulen, et al., Multimodality image registration by maximization of mutual information, IEEE Trans. on Med. Imaging, Vol. 16, pp. 187-198 (1997).

[Mag91] M. Magnusson, R. Lenz, P-E Danielsson. Evaluation of methods for shaded surface display of CT volumes. Comput. Med. Imaging Graph., 15(4):247-256, 1991.

[Mal89] S. Mallat, A theory for multiresolution signal decomposition: the wavelet representation, IEEE Trans. Patt. Analysis and Machine Intelligence, vol. 11, p. 674-693 (1989).

[Mal95] R. Malladi, J. Sethian and B. Vemuri, Shape modeling with front propagation: a level set approach, IEEE Trans. Patt. Ann. Mach. Intelligence, Vol. 17, No. 2, pp. 158-175 (1995).

[Mal96] R. Maliadi, R. Kimmel, D. Adaisteinsson, G. Sapiro, V. Caselles, and J. A. Sethian. A geometric approach to segmentation and analysis of 3-D medical images. in Proc. IEEE Workshop Mathematical Methods in Biomedical image Analysis, 1996,pp. 244--252.

[Mal98] S. Mallat, A Wavelet Tour of Signal Processing (1998).

[Man94] P. Mantey, R. Moorhead, D. Silver and S. Uselton, A View of Visualization: Its Origins, Developments and New Directions, Proc. Visual Data Exploration and Analysis Conf., San Jose, CA, USA, Feb. 7-8 (1994).

[Mar80b] D. Marr and E. Hildreth, Theory of edge detection, Proc. royal Soc., London, vol. 21, pp. 187-217 (1980).

[Mar93] F. Marchak, W. Cleveland, B. Rogowits and C. Wickens, Panel: The psychology of visualization, Proc. IEEE Visualization (VIS'93), San Francisco, CA, USA (1993).

[Mar94] S. R. Marschner, R. J. Lobb. An evaluation of reconstruction filters for volume rendering. In R. Daniel Bergeron, Arie E. Kaufman, editors, Proc. VISUALIZATION'94, pages 100-107, Los Alamitos, CA, 1994. IEEE Computer Society Press.

[Mar98a] H. Margossian, A. Garcia-Ruiz, T. Falcone, J. M. Goldberg, M. Attaran, J. Miller, M. Gagner. Robotically assisted laparoscopic tubal anastomosis in a porcine model: A pilot study. Journal Laproendoscopic and advanced surgical techniques 8:69-73, 1998.

[Mar98b] J. Marescaux, J. M. Clément, V. Tassetti, C. Koehl, S. Cotin, Y. Russier, D. Mutter, H. Delingette, N. Ayache. Virtual Reality Applied to Hepatic Surgery Simulation: The Next Revolution. Ann Surg 228: p627-34, 1998.

[Mar98c] A. Marsh. The telemedical Information Society, Editor for special double issue, Future Generation Computer Systems (FGCS) journal, Volume 14, Numbers 1-2, Jun. 1998

[Mar99] A. Marsh. ITIS-An International Telemedical Information Society, Editor for special issue, Future Generation Computer Systems (FGCS) journal, Volume 15, Number 2, pp131-306, Mar. 1999.

[Mas98] Y. Masutani, T. Schiemann and K-H. Höhne, Vascular Shape Segmentation and Structure Extraction Using a Shape-Based Region-Growing Model, Medical Image Computing and Computer-Assisted Intervention (MICCAI) 98; pages 1242-1249; Cambridge, MA, Springer Lecture Notes in Computer Science 1496 (1998).

[Mau98] C. Maurer, D. Hill, R. Maciunas, et al., Measurement of Intraoperative Brain Surface Deformation Under a Craniotomy, Medical Image Computing and Computer-Assisted Intervention (MICCAI) 98; pages 51-62; Cambridge, MA, Springer Lecture Notes in Computer Science 1496 (1998).

[MCA96] H. P. McAdams, R. Shahidi, V. Argiro, H. Chotas, W. Kurylo, Costa and V. Tapson. Clinical evaluation of perspective surface and volume rendering techniques for performing virtual bronchoscopy. in Proc. Int. Symp. Computer and Communications Systems and Image Guided Diagnosis, CAR'96, Paris, France 1996, pp. 73-77.

[McI93] T. McInerney, D. Terzopoulos. A finite element model for 3D shape reconstruction and nonrigid motion tracking. In Int. Conf. on Computer Vision, ICCV'93, pages 518-523, Berlin, Germany, 1993.

[McI95] T. McInerney, D. Terzopoulos. Medical image segmentation using topologically adaptable snakes. Proc. First International Conference on Computer Vision, Virtual Reality, and Robotics in Medicine (CVRMed'95), Nice, France, April, 1995, in Lecture Notes in Computer Science, Vol. 905, Springer-Verlag, Berlin, 92-101.

[MCI97] T. McInerney, D. Terzopoulos. Medical image segmentation using topologically adaptable surfaces. Proc. First Joint Conference of Computer Vision, Virtual Reality, and Robotics in Medicine and Medical Robotics and Computer-Assisted Surgery (CVRMed-MRCAS'97), Grenoble, France, March, 1997, in Lecture Notes in Computer Science, Vol. 1205, Springer-Verlag, Berlin, 23-32.

[McI98] T. McInerney and R. Kikinis, An Object-Based Volumetric Deformable Atlas for the Improved Localization of Neuroanatomy in MR Images, Medical Image Computing and Computer-Assisted Intervention (MICCAI) 98; pages 861-869; Cambridge, MA, Springer Lecture Notes in Computer Science 1496 (1998).

[Mel97] G. Meller, A typology of simulators for medical educators, J. Digit. Imaging, Vol. 10, No. 3 Supp 1, pp. 194-196 (1997).

[McI99] T. McInerney, D. Terzopoulos. T-Snakes: Topology adaptive snakes. Medical Image Analysis, 1999, in press.

[Men75] B. Mendelson, Introduction to Topology, Allyn and Bacon, Inc., Boston, MA (1975).

[Men92] W. Menhardt. Iconic fuzzy sets for MR image segmentation. In A. E. Todd-Pokropek, Max A. Viergever, editors, Medical Images: Formation, Handling and Evaluation, volume 98 of NATO ASI Series F, pages 579-591. Springer-Verlag, Berlin, 1992.

[Men93] S. Menet, P. Saint-Marc, G. Medioni. Active contour models: Overview, implementation and applications. System, Man and Cybernetics, pages 194-199, 1993.

[Met93] Metaxas, D. Terzopoulos. Shape and non-rigid motion estimation through physics-based synthesis. IEEE Transactions on Pattern Analysis and Machine Intelligence, 15(6):580-591, 1993.

[Mey95] F. Meyer, R. Constable, A. Sinusas and J. Duncan, Tracking myocardial deformation using spatially constrained velocities, Information Proc. in Med. Imaging Kluwer (1995).

[Mey97] F. Meyer and R. Coifman, Brushlets: A tool for directional image analysis and image compression, Applied and computational harmonic analysis, vol. 4, pp. 147-187 (1997).

[Mey98] C. Meyer, J. Boes, B. Kim and P. Bland, Evaluation of control point selection in automatic, mutual information driven 3D warping, in Proc. of the 1998 Medical Image Computing and Computer-Aided Intervention (MICCAI 98) Conference, Springer Lecture Notes in Computer Science 1496; pp. 944-951 (1998).

[MIC98] Proceedings of the 1998 Medical Image Computing and Computer-Aided Intervention (MICCAI 98) Conference, Springer Lecture Notes in Computer Science 1496 (1998).

[Mil93] M. Miller, G. Christensen, Y. Amit and U. Grenander, Mathematical textbook of deformable neuroanatomies, Proc. National Academy of Sciences, Vol. 90, pp. 11944-11948 (1993).

[Mis91] S. K. Mishra, D. B. Goldgof, T. S. Huang. Motion analysis and epicardial deformation estimation from angiography data. In Proc. Computer Vision and Pattern Recognition, pages 331-336. IEEE Computer Society Conference, Jun. 1991. Lahaina, Maui, Hawaii.

[Mit95]M. Mitsuishi, T. Wantanabe, U. Nakanishi, T. Hori, H. Wantanabe, B. Kramer, A Tele-micro-Surgery System Across the Internet with a Fixed Viewpoint/Operation Point. Proc. IEEE Int. Conf. Intelligent Robots and Systems, Los Alamitos, CA, 1995, vol. 2, pp. 178-185.

[Mol98] B. Mollard, S. Lavallée and G. Bettega, Computer Assisted Orthognathic Surgery, Proceedings of the 1998 Medical Image Computing and Computer-Aided Intervention (MICCAI 98) Conference, Springer Lecture Notes in Computer Science 1496; pp 21-29 (1998).

[Mon93] E. Montabord, B. Gibaud, C. Barillot, et al., A hypermedia system to manage anatomical knowledge about the brain, in Proc. Computer Assisted Radiology, H. Lemke, ed.; Springer, Berlin, Germany; pp. 414-419 (1993).

[Mon97] J. Montagnat and H. Delingette, Volumetric Medical Images Segmentation using Shape Constrained Deformable Models, in Computer Vision, Virtual Reality and Robotics in Medicine, pp. 13-22, March (1997).

[Mon98] J. Montagnat and H. Delingette, Globally Constrained Deformable Models for 3D Object Reconstruction, Signal Processing, Vol. 71, No. 2, pp. 173-186 (1998).

[Mon99] E. Monclús, I. Navazo, S. Opi, P. Cano, J. Hueto, J. Pamias, S. Pedraza, X. Vila. Plataforma para la planificaci n y simulaci n de osteotomías maxilares. Congreso Español de Informática Gráfica, CEIG´99. 1999.

[Mer95] J. R. Merril, G. L. Merril, R. Raju, et al. Photorealistic Interactive 3-D graphics in Surgical Simulation. p244-52. In Satava RM, Morgan K, et al Interactive Technology and the New Medical Paradigm for Health Care. IOS Press: Washington DC, 1995.

[Moo98] J. Moody, A. DiGioia, B. Jaramez, et al., Gaugin Clinical Practice: Surgical Navigation for Total Hip Replacement, Medical Image Computing and Computer-Assisted Intervention (MICCAI) 98; pages 421-430; Cambridge, MA, Springer Lecture Notes in Computer Science 1496 (1998).

[Mor93] MER95] J. R. Merril, G. L. Merril, R. Raju, et al. Photorealistic Interactive 3-D graphics in Surgical Simulation. p244-52. In Satava RM, Morgan K, et al Interactive Technology and the New Medical Paradigm for Health Care. IOS Press: Washington DC, 1995.

[Mor98] K. Mori, J.i-. Hassegawa, Y. Suenaga, et al., Automated Labeling of Bronchial Branches in Virtual Bronchoscopy System, Medical Image Computing and Computer-Assisted Intervention (MICCAI) 98; pages 870-878; Cambridge, MA, Springer Lecture Notes in Computer Science 1496 (1998).

[Mro99] L. Mroz, A. Koenig, E. Groeller, Real-Time Maximum Intensity Projection, , in E. Groeller, H. Loeffelmann, and W. Ribarsky, eds.; Data Visualization'99; Springer Wien, pp. 135-144 (1999).

[Mul95] R. Mullick and N. Ezquerra, Automatic Determination of the LV Myocardium in 3D SPECT Imaging, IEEE Trans. Med. Imaging, vol. 14, No. 1, pp. 88-99, March (1995).

[Mul98] M. Mulet-Parada and J. A. Noble, 2D+T acoustic boundary detection in echocardiography, Medical Image Computing and Computer-Assisted Intervention (MICCAI) 98; pages 806-813; Cambridge, MA, Springer Lecture Notes in Computer Science 1496 (1998).

[Mur98] W. Murray, A. Arnold, S. Salinas, et al., Building Biomechanical Models Based on Medical Image Data: An Assessment of Model Accuracy, Medical Image Computing and Computer-Assisted Intervention (MICCAI) 98; pages 539-550; Cambridge, MA, Springer Lecture Notes in Computer Science 1496 (1998).

[Mus90] M. Musen, Knowledge Acquisition in Medicine, Tutorial Notes, Symposium on Computer Applications in Medical Care, Washington, DC, USA (1990).

[Nai97] D. Naidich, J. Lee, S. Garay, et al., Comparison of CT and fiber-optic bronchoscopy in the evaluation of bronchial disease, Amer. J. Radiology, Vol. 148, pp. 1-7 (1997).

[Nak98] T. Nakagohri, F. Jolesz, S. Okuda, et al., "Virtual Endoscopy of Mucin-Producing Pancreas Tumors," Medical Image Computing and Computer-Assisted Intervention (MICCAI) 98; pages 926-933; Cambridge, MA, Springer Lecture Notes in Computer Science 1496 (1998).

[Nap96] S. Napel, G. D. Rubin, C. F. Beaulieu, R. B. Jeffrey, V. Argiro. Perspective volume rendering of cross-sectional images for simulated endoscopy and intraparenchymal viewing.
in Proc. SPIE: Medical Image, Newport Beach, CA, 1996, pp. 1-12.

[Nat91] K. Natarajan, M. Cawley, and J. Newell, A knowledge-based system paradigm for automatic interpretation of CT scans, Medical Informatics, vol. 16, No. 2, pp. 167-181 (1991).

[Nas94a] C. Nastar, N. Ayache. Classification of nonrigid motion in 3d images using physics-based vibration analysis. In IEEE Workshop on Biomedical Image Analysis (WBIA'94), Seattle, USA, Jun. 1994.

[Nas94b] C. Nastar, N. Ayache. Deformable 3D objects: using modes and FFT for a quantitative analysis of non rigid motion. In IEEE Workshop on Object Representation for Computer Vision, New-York, USA, Dec. 1994.

[Nei93] J. Neider, T. Davis, M. Woo, OpenGL Programming Guide. Reading, MA. Addison-Wesley, 1993.

[Neg95] N. Negroponte, Being Digital, MIT Press, Cambridge, MA, USA (1995).

[NEM98ONL] Digital Imaging and Communications in Medicine (DICOM); NEMA; Global Engineering Documents.

[Ney91a] D. Ney, E. K. Fishman. Editing tools for 3D medical imaging. IEEE Comput. Graphics Appl., 11(6):63-70, 1991.

[Ney91b] D. Ney, E. K. Fishman, D. Magid, D. D. Robinson, A. Kawashiina. Three-dimensional volumetric display of CT data: Effect of scan parameters upon image quality. J. Comput. Assist. Tomogr, 15(5):875-885, 1991.

[Nie97] G. Nielson and B. Shriver, eds.; Visualization in Scientific Computing, IEEE CS Press; ISBN 0-8186-7777-5 (1997).

[Nin93] P. Ning, J. Bloomenthal. An evaluation of implicit surface tilers. IEEE Comput. Graphics Appl., 13(6):33-41, 1993.

[Nol95] L. Nolte, L. Zamorano, Z. Jian, et al., Image-Guided insertion of transpedicular scres: a laboratory set-up, Spinevol. 20, pp. 497-500 (1995).

[OBr94] J. O'Brien and N. Ezquerra, Automatic Segmentation of Coronary Vessels in Angiographic Image Sequences Using Temporal, Spatial and Structural Constraints, Proc. 1996 Visualization in Biomedical Computing (VBC94) Conf., SPIE Vol. 2359, No. 25, pp. 25-37; R. Robb et al., eds; Rochester, MN, USA (1994).

[Opp75] A. V. Oppenheim, R. W. Shafer, Digital Signal Processing. Englewood Cliffs, NJ: Prentice-Hall, 1975.

[OTo95] R. O'Toole, B. Jaramaz, A. DiGioia, et al., Biomechanics for preoperative planning and surgical simulations in orthopedics, Comput. Biol. Med. Vol. 25, pp. 183-191 (1995).

[OTo98] R. O'Toole, R. Playter, T. Krummel et al., Assessing Skill and Learning in Surgeons and Medical Students Using a Force Feedback Surgical Simulator, Medical Image Computing and Computer-Assisted Intervention (MICCAI) 98; pages 899-909; Cambridge, MA, Springer Lecture Notes in Computer Science 1496 (1998).

[Pap98] X. Papademetris, J. Rambo, D. Dione, et al., Visually interactive cine-3D segmentation of cardiac mr images, Suppl. to the J. Am. Coll. of Cardiology, vol. 31, No. 2 (Suppl. A), February 1998.

[Par95] J. Park, D. Metaxas and L. Axel, Volumetric deformable models with parameter functions: a new approach to the 3D motion analysis of the LV from MRI-SPAMM, 5th. Int. Conf. Computer Vision, pp. 700-705 (1995).

[Pau92] H. Paul, Image-Directed Robotic Surgery, in Proc. Medicine Meets Virtual Reality (MMVR 92), Aligned Management Associates, San Diego, CA, USA (1992).

[Pec98] W. Peckar, C. Schnörr, K. Rohr, H. S. Stiehl, Non-Rigid Image Registration Using a Parameter-Free Elastic Model, Proc. British Machine Vision Conference (BMVC'98), Southampton/UK, Sept. 14-17, 1998, J. N. Carter, M. S. Nixon, (Eds.), British Machine Vision Association 1998, 134-143.

[Pec99] W. Peckar, C. Schnörr, K. Rohr, H. S. Stiehl, Parameter-Free Elastic Deformation Approach for 2-D and 3-D Registration Using Prescribed Displacements, Journal of Mathematical Imaging and Vision 10 (1999) 143-162.

[Pei92] J. Peifer, E. Garcia, D. Cooke, et al., Visualization of Multimodality Cardiac Imagery, Proc. Visualization in Biomedical Computing (VBC92), Chapel Hill, NC, SPIE 1808, R. Robb, ed.; pp. 225-233 (1992).

[Pen94] X. Pennec, N. Ayache. An O(n^2) algorithm for 3d substructure matching of proteins. In A. Califano, I. Rigoutsos, H. J. Wolson, editors, Shape and Pattern Matching in Computational Biology. Plenum Publishing, 1994.

[Per87] P. Perona and J. Malik, Scale-space and edge detection using anisotropic diffusion, in Proc. IEEE Computer Society Workshop in Computer Vision, pp. 16-22, Nov. (1987).

[Pfl95] B. Pflesser, U. Tiede, K. Heinz Höhne. Towards realistic visualization for surgery rehearsal. In N. Ayache, editor, Computer Vision, Virtual Reality and Robotics in Medicine, Proc. CVRMed'95, volume 905 of Lecture Notes in Computer Science, pages 487-491. Springer-Verlag, Berlin, 1995.

[Pfl98] B. Pflesser, U. Tiede, K. H. Hoehne, Specification, modeling and visualization of arbitrarily shaped cut surfaces in the volume model. In Wells, W. M. et al. ed. : Medical Image Computing and Computer-Assisted Intervention, Proc. MICCAI'98. Lecture Notes in Computer Science 1496, Springer-Verlag, Berlin, 1998, 853-860.

[Pha99] D. L. Pham, J. L. Prince, An Adaptive Fuzzy C-Means Algorithm for Image Segmentation in the Presence of Intensity Inhomogeneities Pattern Recognition Letters, vol. 20, no. 1, pp. 57-68, 15-Jan., 1999.

[Piz90] S. Pizer, T. Cullip and R. Fredericksen, Toward interactive object definition in 3D scalar images, 3D Imaging in Medicine, Vol. F, No. 60, pp. 83-105 (1990).

[Pom90] A. Pommert, U. Tiede, G. Wiebecke, K. H. Höhne. Surface shading in tomographic volume visualization: A comparative study. In First

Conference on Visualization in Biomedical Computing, Proc. VBC'90, pages 19-26. IEEE Computer Society Press, Los Alamitos, CA, 1990.

[Pom91] A. Pommert, W-J Höltje, N. Holzknecht, U. Tiede, K. H. Höhne. Accuracy of images and measurements in 3D bone imaging. In Heinz U. Lemke, Michael L. Rhodes, C. Carl Jaffe, Roland Felix, editors, Computer Assisted Radiology, Proc. CAR'91, pages 209-215. Springer-Verlag, Berlin, 1991.

[Pom92] A. Pommert, M. Bomans, K. H. Höhne. Volume visualization in magnetic resonance angiography. IEEE Comput. Graphics Appl., 12(5):12-13, 1992.

[Pom94] A. Pommert, R. Schubert, M. Riemer, T. Schiemann, U. Tiede, K. H. Höhne. Symbolic modeling of human anatomy for visualization and simulation. In Richard A. Robb, editor, Visualization in Biomedical Computing 1994, Proc. SPIE 2359, pages 412-423, Rochester, MN, 1994.

[Pou98a] C. Poupon, J.-F. Mangin, V. Frouin, et al., Regularization of MR Diffusion Tensor Maps for Tracking Brain White Matter Bundles, MICCAI 98, pp. 489-498; Cambridge, MA, USA; Springer Lecture Notes Series in Computer Science 1496 (1998).

[Pou98b] B. Poulouse, M. Kutka, M. Mendoza-Sagaon, et al., Human Versus Robotic Organ Retraction During Laparoscopic Nissen Foundoplication, MICCAI 98, pp. 197-206; Cambridge, MA, USA; Springer Lecture Notes Series in Computer Science 1496 (1998).

[Pra98] R. Prager, A. Gee and L. Berman, Real-Time Tools for Freehand 3D Ultrasound, Medical Image Computing and Computer-Assisted Intervention, MICCAI 98, pp. 1016-1023; Cambridge, MA, USA; Springer Lecture Notes Series in Computer Science 1496 (1998).

[Pri92] J. Prince and E. McVeigh, Motion estimation from tagged mr image sequences, IEEE Trans. Med. Im., vol. 11, pp. 238-249 (1992).

[Pro97a] J. Proccaz, E. Grimson, R. Mosges, Eds., Proceedings of the First Joint Conference on Computer Vision, Virtual Reality and Robotics in Medicine and Medical Robotics and Computer-Assisted Surgery. Grenoble, France: Springer-Verlag, 1997.

[Pro97b] E. Promayon, P. Baconnier, C. Puech, Physically-based model for simulating the human trunk respiration movements, in Proceedings of the First Joint Conference on Computer Vision, Virtual Reality and Robotics in Medicine and Medical Robotics and Computer-Assisted Surgery, J. Proccaz, E. Grimson, R. Mosges, Eds. Grenoble, France: Springer-Verlag, 1997, pages 379-388.

[Pui97a] A. Puig. Contribution to volume modeling and visualization in medicine: Cerebral blood vessels analysis. PhD Extended Abstract, LSI, Polytechnical University of Catalunya, Spain 1997.

[Pui97b] A. Puig. D. Tost, I. Navazo. An Interactive Cerebral Blood Vessel Exploration System. Proceedings IEEE Visualization 1997.

[Rai98] M. Raibert, R. Playter, T. M. Krummel. The use of a virtual reality haptic device in surgical training Acad Med 73: p596-97, 1998.

[Ras86] J. Rasmussen, Information Processing and human-machine interaction: an approach to cognitive engineering," Elsevier Publishers, New York (1986).

[Rho97] M. Rhodes, Computer Graphics and Medicine: A Complex Partnership, IEEE Computer Graphics and Applications, Vol. 17, No. 1, pp. 22-29 (1997).

[Rob89] R. Robb and C. Barillot, "Interactive Display and Analysis of 3D Medical Images, IEEE Trans. Med. Imaging, MI-8 (3); pp. 217-226 (1989).

[Rob91] M. L. Rhodes. Computer graphics in medicine: The past decade, IEEE Comput. Graphics Appl., vol. 11, no. 1, pages 52-54, 1991.

[Rob96] R. Robb and D. Hanson, The ANALYZE software system for visualization and analysis in surgery simulation, in Computer Integrated Surgery, R. Taylor, ed., Chapter 10, MIT Press, Cambridge, MA, USA (1996).

[Rog90] E. Rogers, R. Arkin, M. Baron, N. Ezquerra and E. Garcia, "Visual Protocol collection for the Enhancement of the Radiological Diagnostic Process, Proc. IEEE Vis. in Biomed. Comp. Conf., pp. 208-215, Atlanta, GA, USA, May (1990).

[Roh97] R. Rohling, A. Gee and L. Berman, Three-dimensional spatial compounding of ultrasound images, Medical Image Analysis, Vol. 1, No. 3, pp. 177-193 (1997).

[Roh98] K. Rohr. Image Registration Based on Thin-Plate Splines and Local Estimates of Anisotropic Landmark Localization Uncertainties, Proc. First Internat. Conf. on Medical Image Computing and Computer-Assisted Intervention (MICCAI'98), Massachusetts Institute of Technology (MIT), Cambridge/MA, USA, Oct. 11-13, 1998, Lecture Notes in Computer Science 1496, W. M. Wells, A. Colchester, S. Delp (Eds.), Springer Verlag Berlin Heidelberg 1998, 1174-1183.

[Ron89] J. Rong, R. Collerec et al., "Model-guided automatic frame-to-frame segmentation in digital subtraction angiography," SPIE Vol. 1137, April (1989).

[Ron91] C. Ronse and H. Heijmans, "The Algebraic Basis of Math. Morphology II. Openings and Closings," CVGIP: Image Understanding, Vol. 54, No. 1, pp. 74-97, July (1991).

[Rot95] K. Rohr. Image Registration Based on Thin-Plate Splines and Local Estimates of Anisotropic Landmark Localization Uncertainties, Proc. First Internat. Conf. on Medical Image Computing and Computer-Assisted Intervention (MICCAI'98), Massachusetts Institute of Technology (MIT), Cambridge/MA, USA, Oct. 11-13, 1998, Lecture Notes in Computer Science 1496, W. M. Wells, A. Colchester, S. Delp (Eds.), Springer Verlag Berlin Heidelberg 1998, 1174-1183.

[Rot98] ROT98] S. H. M. Roth, M. H. Gross, S. Turello, F. R. Carls. A Bernstein-Bézier Based Approach to Soft Tissue Simulation. Proceedings of the Eurographics'98 (Lisbon, Portugal, Sept. 2-4, 1998), COMPUTER GRAPHICS Forum, Vol. 17, No. 3, C285-C294, 1998.

[Ros82] A. Rosenfeld, A. C. Kak. Digital Picture Processing. Academic Press, New York, 1982.

[Rub96] G. D. Rubin, C. F. Beaulieu, V. Argiro, H. Ringl, A. Norbash, J. Feller, M. Dake, R. B. Jeffrey, S. Napel. Perspective volume rendering of CT and MR images: Applications for endoscopic imaging. In Radiology, vol 199, pp. 321-330,1996
[Sak96] B. P. Sakas, G. Special issue on medical visualization. volume 20, pages 759-838. Pergamon, Nov. 1996.

[Sak97] G. Sakas and A. Pommert, Advanced Applications in Volume Visualization Methods in Medicine, STAR Report, Proceedings Eurographics 98, pp. 101-143 (1998).

[Sak98] SAK98] G. Sakas, S. Walter. TeleInViVo - A 3D Ultrasound TeleMedical Workstation, Conference: International Congress on New Technology in Surgery: Surgery Meets High-Tech in the Information Age, Muenchen. 1998.

[Sam97] S. Samarasekera, J. K. Udupa, Y. Miki, R. I. Grossman, A new computer assisted method for enhancing lesion quantification in multiple sclerosis, J. of Comp. Assist. Tomo. vol. 21(1), pp. 145-151, 1997.

[Sas96] S. S. Sastry, M. Cohn, and F. Tendick. Millirobotics for remote, minimally-invasive surgery. in Proc. Int. Workshop on Medical Robotics, Vienna, Austria, 1996, pp. 169-186.

[Sat93] SAT93] R. M. Satava. Virtual Reality Surgical Simulator: The First Steps Surg Endosc 7: 203-05, 1993.

[Sat95] R. M. Satava. Virtual Reality and Telepresence for Military Medicine. Comput. Biol. Med., vol. 25, no. 2, pp. 229-236, 1995.

[Sat97a] Y. Sato, S. Kakajima, H. Atsumi, et al., 3D multiscale line filter for segmentation and visualization of curvilinear structures in medical images, in Proc. CVRMed-MRCAS 97, J. Troccaz, E. Grimson and R. Mosges, eds.; berling; Springer-Verlag Lecture Series in Computer Science, pp. 213-222 (1997).

[Sat98a] Y. Sato, S. Nakajma,N. Shiraga, et al., Three-dimensional multiscale line filter for segmentation and visualization of curvilinear structures in medical images, Medical Image Analysis, Vol. 2, No. 2, pp. 143-168, June (19998).

[Sat98b] R. Satava, Current and Future Applications of Virtual Reality for Medicine, Proc. IEEE, vol. 86, No. 3, March (1998).

[Sat99] R. M. Satava , S. B. Jones. Medical Applications of Virtual Reality. Handbook of Virtual Environment Technology, Kay Stanney (Ed.) by Lawrence Erlbaum Assoc., Inc. December, 1999.

[Sch87] B. Schneiderman, Designing the User Interface: Strategies for Effective Human-Computer Interaction, Addison Wesley (1987)

[Sch92A] T. Schiemann, M. Bomans, U. Tiede, K. H. Höhne. Interactive 3D-segmentation. In Richard A. Robb, editor, Visualization in Biomedical Computing II, Proc. SPIE 1808, pages 376-383, Chapel Hill, NC, 1992.

[Sch92B] W. J. Schroeder, J. A. Zarge, William E. Lorensen. Decimation of triangle meshes. Comput. Graphics, 26(2):65-70, 1992.

[Sch93] T. Schiemann, B. Dippold, R. Schmidt, A. Pommert, M. Riemer, R. Schubert, U. Tiede, K. H. Höhne. 3D visualization for radiotherapy treatment planning. In Heinz U. Lemke, Michael L. Rhodes, C. Carl Jaffe, Roland Felix, editors, Computer Assisted Radiology, Proc. CAR'93, pages 669-675. Springer-Verlag, Berlin, 1993.

[Sch94] A. Schweikard, J. Adler, J. C. Latombe. Motion planning in stereotaxic radiosurgery. to appear in IEEE Trans. on robotics and automation, 1994.

[Sch95] A. Schweikard, J. R. Adier, and J. C. Latombe. Motion planning in stereotaxic radiosurgery. In IEEE Trans. Robot. Automat., vol. 9, no. 6, pp. 764-774, 1993; see also Computer-Integrated Surgery, R. H. Taylor et al, Eds. Cambridge, MA: MIT Press, 1995, pp. 693-706.

[Seb93] R. Sebuhert, K. H. Höhne, A. Pommert, M. R. Schiemann, U. Tiede. Spatial knowledge representation for visualization of human anatomy and function. In Harrison H. Barrett, A. F. Gmitro, editors, Information Processing in Medical Imaging, Proc. IPMI'93, volume 687 of Lecture Notes in Computer Science, pages 168-181. Springer-Verlag, Berlin, 1993.

[Ser82] J. Serra. Image Analysis and Mathematical Morphology. Academic Press, 1982.

[Ser88] J. Serra, Introduction to Morphological Filters, in Image Analysis and Math. Morphology; Vol. 2, Theoretical Advances, J. Serra, ed. Academic Press, London (1988).

[Ser98] L. Serra, R. Kockro, C. G. Guan et al., Multimodal Volume-Based Tumor Neurosurgery Planning in the Virtual Workbench, Medical Image Computing and Computer Assisted Intervention, MICCAI 98; Cambridge, MA, USA; W. Wells, A. Colchester, and S. Delp, eds; pp. 1006-1015; Springer Lecture Notes Series in Computer Science 1496 (1998).

[Sha95] R. Shahidi, R. Mezrich and D. Silver. Proposed simulation of volumetric image navigation using a surgical microscope. J. Image Guided Surgery, vol. 1, pp. 249-265, 1995.

[Sha98] R. Shahidi, R. Tombropoulis, R. P. Grzeszczuk, Clinical Applications of Three-Dimensional Rendering of Medical Data Sets. Proceedings of the IEEE, Vol. 86, No. 3, March 1998.

[She98] F. Sheehan, E. Bolson, R. Martin, et al., Quantitative Three Dimensional Echocharadiography: Methodology, Validation and Clinical Applications, Medical Image Computing and Computer Assisted Intervention, MICCAI 98; Cambridge, MA, USA; W. Wells, A. Colchester, and S. Delp, eds; pp. 102-109; Springer Lecture Notes Series in Computer Science 1496 (1998).

[Shu92] Shung, et. al. Principles of Medical Imaging. Academic Press 1992.

[Sin98] A. Singh, D. Goldgof, D. Terzopoulos, eds.; Deformable Models in Medical Image Analysis, IEEE Comp. Soc. Press, Los Alamitos, CA, USA; ISBN 0-8186-8521-2 (1998).

[Smi94]K. R. Smith, K. J. Frank, and R. D. Bucholtz. The neurostation: A highly accurate, minimally invasive solution to frameless stereotactic neurosurgery. Comput. Med. Imaging Graph., vol. 18, no. 4, pp. 247-256, 1994.

[Sof98] Z. Sofreman and D. Blythe, Advanced Graphics Behind Medical Virtual Evolution of Algorithms, Hardware, and Software Interfaces, in Proc. of the IEEE, vol. 86, No.3, pp. 531-534, March (1998).

[Spi92] V. Spitzer, D.Whitlock, Electronic Imaging of the Human Body. Data storage and interchange format standards, in Proc. Electronic Imaging of the Human Body Working Group, M. Vannier, ed.; pp. 66-68, March 0-11 (1992).

[Sta89] K. Stach, S. Sakamoto, K. Baba, Development of an ultrasound system for 3d-reconstruction of the fetus. volume 17, 1989.

[STA92] L. Staib, J. Duncan. Deformable Fourier models for surface finding in 3D images. In R. Robb, editor, Visualization in Biomedical Computing, volume 1808, pages 90-104. SPIE, 1992. Chapel Hill.

[Sta96] A. State, M. Livingston, G. Hirtoa, et al, Techniques for augmented reality systems: Realizing ultrasound-guided needle biopsies, Proc. SIGGRAPH 96, New Orleans, Louisiana, USA, pp. 439-446 (1996).

[Ste94] H. Steiner, A. Staudach, D. Spitzer and H. Schaffer, Three-dimensional ultrasound in obstetrics and bynecology: techniques, possibilities and limitations, Human Reproduction, Vol. 9, No. 9, pp. 1773-1778 (1994).

[StJ98] P. St-Jean, A. F. Sadikot, L. Collins, D. Clonda, R. Kasrai, A. C. Evans, T. M. Peters.

Automated atlas integration and interactive three-dimensional visualization tools for planning and guidance in functional neurosurgery. IEEE Trans Med Imaging 1998 Oct 17:5 672-80.

[Str97] J. Streicher J, W. J. Weninger, G. B. Müller, External Marker Based Automatic Congruencing: A New Method of 3D-Reconstruction From Serial Sections. The Anatomical Record 248: 583-602. 1997.

[Stu96] C. Studholme, D. L. G. Hill, D. J. Hawkes. Automated 3-D registration of MR and CT images of the head. Med. Image Anal., 1(2):163-175, 1996.

[Sty91] M. Stytz, G. Frieder, O. Frieder. Three-dimensional medical imaging: algorithms and computer systems. ACM Computer Surveys, 23(4):421-499, Dec. 1991.

[Sub96] G. Subsol, J. Thirion and N. Ayache, Application of an automatically built 3D morphometric atlas: Study of cerebral ventricle shape, in Proc. Visualization in Biomed. Computing (VBC'96), Hamburg, Germany, pp. 373-382, LNCS 1131; pp. 373-382 (1996).

[Sze96] R. Szeliski and S. Lavallée, Matching 3D anatomical surfaces with non-rigid deformations using octree splines, Int. J. Comp. Vision, Vol. 18, No. 2, pp. 171-186 (1996).

[Sut94] C. Sutherland, S. Bresina, D. Gayou, Use of general purpose mechanical computer assisted engineering software in orthopedic surgical planning: advantages and limitations, Comput. Med. Imaging Graph., Vol. 18, pp. 435-442 (1994).

[Tay95] R. H. Taylor, S. Lavallée, G. C. Burdea, R. Mosges. Computer Integrated Surgery: Technology and Clinical Applications. MIT Press, Cambridge, MA, 1995.

[Tay96] R. Taylor, S. Lavallée, G. Burdea and R. Mosges, Computer Integrated Surgery. Technology and Clinical Applications, MIT Press (1996).

[Tek95] H. Tek and B. Kimia, Volumetric segmentation of medical images by three-dimensional bubbles, in Proc. Workshop Physics-Based Modeling in Computer Vision, pp. 9-16 (1995).

[Ter87] D. Terzopoulos, A. Witkin, M. Kass. Symmetry seeking models for 3D object reconstruction: Active contour models. In Proceedings of the first International Conference on Computer Vision (ICCV 87), London, Jun. 1987.

[TER91] D. Terzopoulos, D. Metaxas. Dynamic 3-D models with local and global deformations: Deformable superquadrics. IEEE Transactions on Pattern Analysis and Machine Intelligence, 13(7):703-714, 1991.

[TER92] D. Terzopoulos, R. Szeliski. Tracking with Kalman snakes. In A. Blake, A. Yuille, editors, Active Vision, chapter 1. MIT-Press, 1992.

[TER93] D. Terzopoulos, K. Waters. Analysis and synthesis of facial image sequences using physical and anatomical models. IEEE Transactions on Pattern Analysis and Machine Intelligence

[Tho96] P. Thompson and A. Toga, A surface-based technique for warping 3D images of the brain IEEE Trans. Med. Imaging, Vol. 15, No. 4, pp. 401-417 (1996).

[Tie90] U. Tiede, K. H. Höhne, M. Bomans, A. Pommert, M. Riemer, G. Wiebecke. Investigation of medical 3D-rendering algorithms. IEEE Comput. Graphics Appl., 10(2):41-53, 1990.

[TIE96] U. Tiede, T. Schiemann, K. H. Höhne. Visualizing the Visible Human. IEEE Comput. Graphics Appl., 16(1):7-9, 1996.

[TIE98] U. Tiede, T. Schiemann, K. H. Hoehne, High quality rendering of attributed volume data. In Ebert, D. et al. ed. : Proc. IEEE Visualization 1998. IEEE Computer Society Press, Los Alamitos, CA, 1998, 255-262.

[Toc98] L. Tockus, L. Joskowicz, A. Simkin, C. Milgrom, Computer-Aided Image-Guided Bone Fracture Surgery: Modeling, Visualization, Preoperative Planning, 1st Int. Conf. on Medical Computing and Computer-Assisted Intervention, Lecture Notes in Computer Science 1496, Elsevier, Wells et al eds. 1998.

[Tog96] A. W. Toga, J. C. Mazziotta. Brain Mapping. Academic Press, San Diego, CA, 1996.

[Tom96] R. Tombropoulos, J.-C. Latombe, and J. R. Adler. A general algorithm for beam selection in radiosurgery. In Proc. Int. Workshop Medical Robotics, Vienna, Austria, 1996, pp 910-998.

[Tot93] T. Totsuka, M. Levoy. Frequency domain volume rendering. Comput. Graphics, pages 271-278, 1993.

[Tre96] R. B. Trelease. Toward virtual anatomy: a stereoscopic 3-D interactive multimedia computer program for cranial osteology. Clin Anat 1996 9:4 269-72.

[Tre98a] G. Treece, R. Prage, A. Gee and L. Berman, Fast surface and volume estimation from non-parallel cross-sections, for freehand 3-D ultrasound, Technical Report 326, Cambridge university Engineering Department, July (1998).

[Tre98b] R. B. Trelease. The virtual anatomy practical: a stereoscopic 3D interactive multimedia computer examination program. Clin Anat 1998 11:2 89-94.

[Tro96] J. Troccaz, Y. Delnondedieu. Robots in Surgery. Proc. Int. Workshop Medical Robotics, Vienna, Austria, 1996, pp. 161-168.

[Udu91] J. Udupa and G. Herman, eds.; 3D Imaging in Medicine, CRC Press, Boca Raton, FL, USA (1991).

[Udu94a] J. Udupa, Multidimensional Digital Boundaries, CVGIP: Graphical Models and Image Processing; Vol. 56, pp. 311-323 (1994).

[Udu94b] J. K. Udupa, D. Odhner, S. Samarasekera, R. Goncalves, K. Iyer, K. Venugopal, S. Furuie, 3DVIEWNIX: An open, transportable, multidimensional, multimodality, multiparametric imaging software system, SPIE Proc. vol. 2164, pp. 58-73, 1994.

[Udu96] J. K. Udupa, S. Samarasekera, Fuzzy connectedness and object definition: Theory, algorithms, applications in image segmentation, Graphical Models and Image Processing, vol. 58(3), pp. 246-261, 1996.

[Udu97A] J. K. Udupa, D. Odhner, J. Tian, G. Holland, L. Axel, Automatic clutter-free volume rendering for MR angiography using fuzzy connectedness, SPIE Proc. vol. 3031, pp. 114-119, 1997.

[Udu97B] J. K. Udupa, L. Wei, S. Samarasekera, Y. Miki, M. A. van Buchem, R. I. Grossman, Multiple sclerosis lesion quantification using fuzzy connectedness principles, IEEE Trans. Med Imaging, vol. 16(5), pp. 598-609, 1997.

[Ull88] J. D. Ullman, Principles of Database and Knowledge-Base Systems, Volume 1, Computer Science Press, Rockville, Maryland (1988).

[Vai97] M. Vaillant, C. F. Beaulieu, V. Argiro, H. Ringl, A. Norbash, J. Feller, M. Dake, R. B. Jeffrey, S. Napel, Perspective volume rendering of CT and MR images: Applications for endoscopic imaging, Radiology, vol. 199, pp. 321-330, 1996.

[Van93a] C. VanOverveld and B. Wyvill, Shrinkwrap: an adaptive algorithm for polygonizing an implicit surface, Tech. Report 95/14/19; U. of Calgary, Dept. of Computer Science, Canada (1993).

[Van93b] P. van der Elsen, E.-J. Pol, and M. Viergever, Medical Image Matching: A review with classification, IEEE Eng. Med. Biol. Magazine, Vol. 12, No. 1, pp. 26-39 (1993).

[Van96] M. Vannier and J. Marsh, Three-Dimensional imaging, surgical planning and image-guided therapy, Rad. Cin. North Am., Vol. 34; pp. 545-563 (1996).

[Vem93] B. Vemuri, A. Radisavljevic, C. Leonard. Multiresolution stochastic 3D shape models for image segmentation. In H. H. Barrett, A. F. Gmitro, editors, Information Processing in Medical Imaging, pages 62-76, Flagstaff, Arizona USA, Jun. 1993. IPMI'93, Springer-Verlag.

[Vem98] B. C. Vemuri, S. Huang, S. Sahni, C. M. Leonard, C. Mohr, R. Gilmore, J. Fitzsimmons, An efficient motion estimator with application to medical image registration, Medical Image Analysis, 2(1), 1998, pages 79-98.

[Vin91] L. Vincent and P. Soille, Watershed in digital spaces: an efficient algorithm based on immersion simulations, IEEE Trans. on Pattern Analysis and Machine Intelligence, Vol. 13, No. 6, pp. 583-598, June (1991).

[Vin96] D. J. Vining, K. Liu, R. H. Choplin, E. F. Haponik, Virtual bronchoscopy: Relationships of virtual reality endobronchial simulations to actual bronchoscopic findings, Chest, vol. 109, pp. 549-553. 1996.

[Vin97] D. Vining, D. Stelts, D. Ahn, P. Hemler, et al., Freeflight: A Virtual endoscopy system, in Proc. CVRMed-MRCAS 97, Grenoble, France; pp. 413-416 (1997).

[Wal91] A. Wallin. Constructing isosurfaces from CT data. IEEE Comput. Graphics Appl., 11 (6):28-33, 1991.

[Wal95] S. Walter, G. Sakas. Extracting surfaces from fuzzy 3d-ultrasonic data. pages 465-474. Addison Wesley, Aug. 1995.

[Wat93] A. Watt, 3D Computer Graphics. Reading, MA: Addison-Wesley, 1993.

[Wat95] E. Watanabe, The nueronavigator: A computer-controlled navigation system in neurosurgery. Computer-Integrated Surgery, R. H. Taylor et al., Eds. Cambridge, MA: MIT Press, 1995, pp 319-327.

[Wel96] W. M. Wells III, P. Viola, H. Atsumi, S. Nakajima, R. Kikinis. Multi-modal volume registration by maximization of mutual information. Med. Image Anal., 1(1):35-51, 1996.

[WEN98] W. J. Weninger, W. J., S. Meng, J. Streicher, G. B. Müller. 1998. A new episcopic method for rapid 3-D reconstruction: applications in anatomy and embryology. Anat. Embryol. 197: 341-348.

[Wie96] G. Wiet, D. Strendney, R. Yagel, et al., Cranial base tumor visualization through high-performance computing, in Proc. Med. Meets Virtual Reality IV, S. Weghorst, H. Siebur and K. Morgan, eds.; San Diego, CA, USA; pp. 43-59; IOS Press (1996).

[Wie97] G. J. Wiet, R. Yagel, D. Stredney, P. Schmalbrock, D. J. Sessanna, Y. Kurzion, L. Rosenburg, M. Levin, K. Martin, A volumetric approach to virtual simulation of functional endoscopic sinus surgery, in Proceedings of Medicine Meets Virtual Reality 5, K. S. Morgan, H. M. Hoffman, D. Stredney, S. J. Weghorst, Eds. San Diego, CA: IOS Press, 1997, pp 167-179.

[Wil90] J. Wilhems, A. van Gelder. Topological considerations in isosurface generation. Comput. Graphics, 24(5):79-86, 1990.

[Win92] P. H. Winston. Artificial Intelligence. Addison-Wesley, Reading, MA, 3. edition, 1992.

[Wu90] Z. Wu and R. Leahy, Tissue classification in MR images using hierarchical segmentation, in Proc. IEEE Medical Imaging, pp. 1410-1414 (1990).

[Xio96] J. Xiong, J-H. Gao, J. Lancaster and P. Fox, Assessment and optimization of functional MRI analyses, Human Brain Mapping, Vol. 4, pp. 153-167 (1996).

[Xu98a] C. Xu, J. L. Prince, Snakes, Shapes, and Gradient Vector Flow, IEEE Transactions on Image Processing, vol. 7, no. 3, pp. 359-369, Mar. 1998.

[Xu98b] C. Xu, J. L. Prince, Generalized Gradient Vector Flow External Forces for Active Contours, Signal Processing, vol. 71, no. 2, pp. 131-139, Dec. 1998.

[Yan98] Z. Yaniv, L. Joskowicz, A. Simkin, M. Garza-Jinich, C. Milgrom, Fluoroscopic Image Processing for Computer-Aided Orthopedic Surgery, 1st Int. Conf. on Medical Computing and Computer-Assisted Intervention, Lecture Notes in Computer Science 1496, Elsevier, Wells et al eds. 1998.

[Yas90] T. Yasuda, Y. Hashimoto, S. Yokoi, J. Toriwaki. Computer system for cranialfacial surgical planning based on CT images. IEEE Trans. Med. Imaging, MI-9(3):270-280, 1990.

[You97] S. You, L. Hong, M. Wan, K. Junyaprasert, A. Kaufman, S. Muraki, Y. Zhou, M. Wax, Z. Liang. Interactive Volume Rendering for Virtual Colonoscopy. Proc. IEEE Visualization'97, Oct. 1997, 433-436.

[You95] A. A. Young, D. L. Kraitchman, L. Dougherty, and L. Axel. Tracking and finite element analysis of stripe deformation in magnetic resonance tagging. IEEE Transactions on Medical Imaging, 14(3):413-421, September 1995.

[Zha93] Z. Zhang. Iterative point matching for registration of free-form curves and surface. Int. Journal of Computer Vision, 1993. to appear, research report available at INRIA, Sophia-Antipolis.

[Zah95] C. Zahlten et al., Reconstruction of branching blood vessels from CT-data, 5th. Eurographics Workshop on Visualization in Scientific Computing, pp. 41-52 (1995).

[Zon98] X. Zon, A. Laine, and E. Geiser, Speckle Reduction and Contrast Enhancement of Echocardiograms via Multiscale Non-Linear Processing, IEEE Tran. Medical Imaging, Vol. 17., pp. 532-540 (1998).