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Clinical Applications of Computer Aided Visualization

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***Abstract*:** The clinical applications of computer aided three-dimensional (3D) data visualization are now numerous. In this paper, we describe the importance of visualization in clinical applications and the methods that are appropriate to particular specialisations. We discuss the requirements of some of these clinical specialisations and describe how developments have taken place over the years to meet these both in terms of new computer algorithms and hardware. We present some selected examples of major clinical applications of data visualization, and end with a note on social, legal and ethical implications.

***Keywords* :** 3D visualization, surgery, volume rendering, augmented reality.

1. Introduction

The use of data visualization has had a growing influence in some clinical specialities over the past twenty years. Certain physical properties of the human anatomy are now commonly sampled over three dimensions by a number of modern medical imaging systems. Computerised Tomography (CT) scanners for example sample the X-ray absorption coefficient, Magnetic Resonance Imaging (MRI) scanners sample emission of radio frequencies after excitation giving measures of proton density and chemical environment. Ultrasound scanners with 3D spatial trackers record the distribution of discontinuities in the speed of sound. Some experimental systems sample the electrical conductivity of tissue. Rotating gamma cameras, Positron Emission Tomography (PET) and Single Photon Emission Computed Tomography (SPECT) systems measure the 3D distribution of radioactive substances within the tissues, providing data for the visualization of physiological processes. All of these systems produce a measure of the distribution of the physical property within the anatomy, and a numerical output for a series of sampled volume elements throughout the anatomical volume examined. These volume elements have become known as *voxels*. The 3D anatomy or function is therefore represented in the output of these imaging systems as a collection of numerical values associated with voxels in an ordered geometrical arrangement. There is also a class of optical scanners, which is designed specifically to record the external surface anatomy, particularly the shape of the face. These systems produce sets of surface co-ordinates that require visualization for their appreciation and analysis. In addition, it is beneficial in planning radiotherapy treatment to be able to visualize the distribution of calculated radiation doses within the tissues. The radiation doses are computed from physical parameters related to the disposition of internal or external sources of ionising radiation.

Most medical imaging systems include some form of electronic visualization. Usually these are video display units (VDUs) together with a system for converting the numerical values into video signal amplitudes. They commonly present a two dimensional 'slice' of anatomical data as a grey level video image. In this paper, we are not concerned with this aspect of visualization, but rather with methods for presenting anatomical information in a three-dimensional format. Early examples of this came soon after the introduction of CT scanners (Herman and Liu, 1979).

2. Techniques for Visualization in Clinical Applications

A number of visualization methods are used for anatomical data. The two most common are known as surface rendering and volume rendering.

2.1 Surface Rendering

In the case of optical surface scanners, structured co-ordinate point sets are produced over an anatomical surface. This represents perhaps the simplest data set to deal with. Triplets of data points are generally grouped as the vertices of adjacent triangles that connect to make up the entire surface. The triangular surface patches are known as *facets or polygons.* Graphics techniques for displaying a surface tessellated in this manner are well established, and many algorithms are publicly available (Harrington, 1987).

The display of surfaces from volume data requires pre-processing. To apply surface rendering to three-dimensional data sets consisting of voxels, faceted surfaces are first derived from the voxel values and these are then rendered.

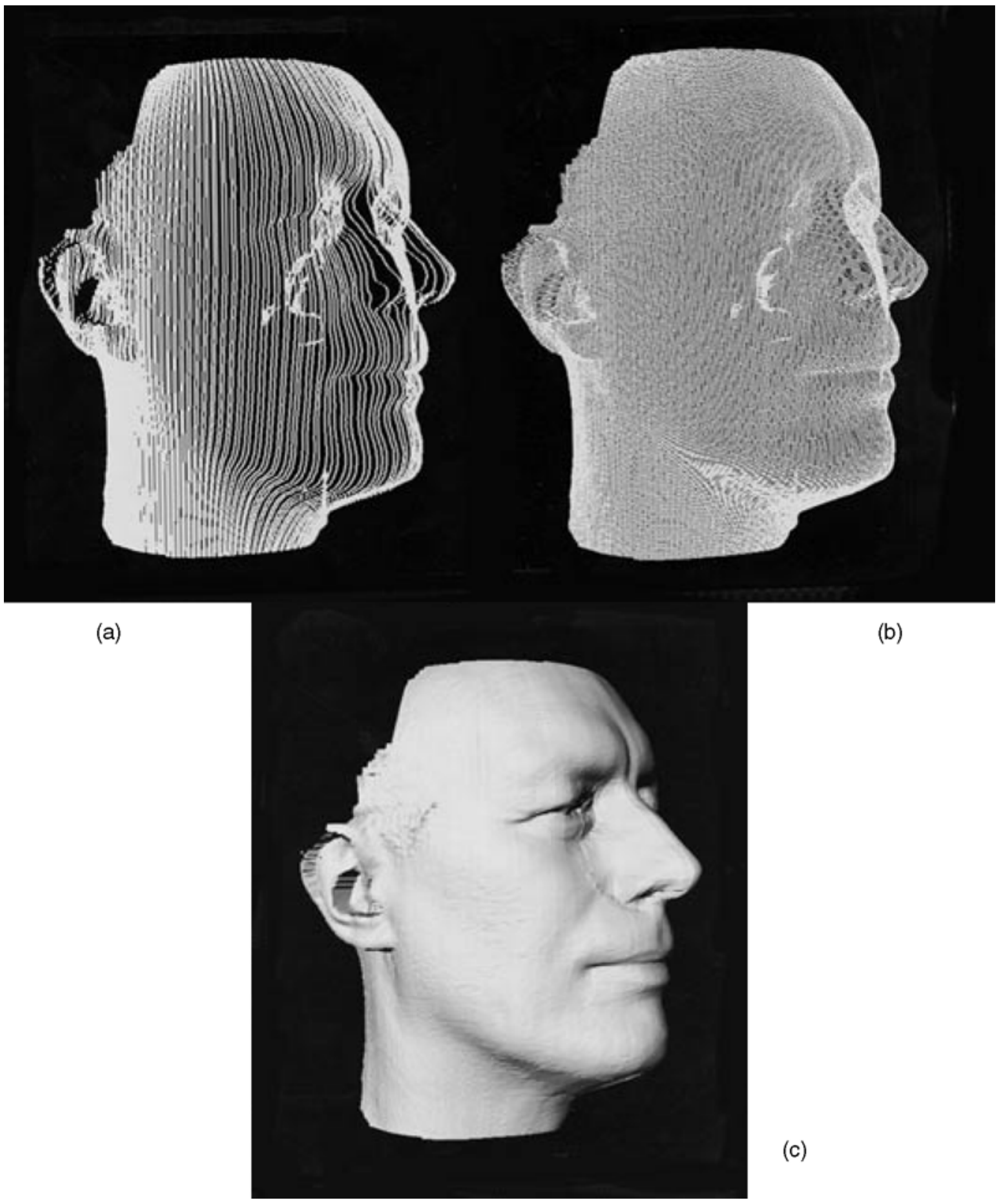


Fig. 1. (a) The raw profile data from optical scan of a face, (b) Derived triangular facets and (c) The rendered facial surface.

The properties of voxels containing anatomical surfaces must first be decided, and voxels with these properties are then processed. Usually the voxels are considered to lie on a surface if they are connected and all have an associated property lying within a given range of values. The derived surfaces are thus *isosurfaces*, and usually in medical image data are selected to correspond to the surfaces of anatomical structures or to surfaces of equal functional activity.

Geometric primitives are also derived from the volumetric data by processes such as contour tracing, surface extraction or border following. Alternatively, the voxels belonging to anatomical parts may be isolated from the full data set by applying thresholds to the data values associated with them. This extraction of tissue topology has become known as *segmentation*.

The derived geometric primitives (such as polygon meshes or contours) are then rendered for display using conventional computer graphics techniques. The surface abstraction may go only as far as deriving a family of polygons to represent an isosurface for example by the application of the 'Marching Cubes' algorithm (Lorensen and Cline, 1987). However, abstraction may go to the extent of deriving algebraic splines to fit the surface. The degree of pre-processing in this method represents a serious computational load, and results in rigid frameworks that are not convenient for certain types of clinical applications. The advantage of the method is that an extracted polygonal surface may be displayed at interactive rates on a modern Personal Computer (PC). It is therefore useful for preparing modern multimedia teaching material. Surface derivation is also used in modelling and the automatic milling of replicas of anatomical parts using numerically controlled milling machines.

Figure 1(c) shows the rendering of a facial surface that is made up of a large set of triangular facets that are also shown in Fig. 1(b). Figure 1(a) shows the raw profile data. This type of image can be produced using data from an optical scan of the face.

Intermediate solutions for volume data sets, which do not explicitly derive geometric surface primitives, require less pre-processing. These may, for example, involve calculations of a set of surface normals distributed over the notional boundary between tissue types, since these are sufficient to calculate a rendition of the surface (Hohne and Bernstein, 1986). The surface normals are derived directly from the voxel values neighbouring the surface using the principle that the maximum spatial gradient of these values will be perpendicular to the surface between two kinds of tissue. These derived surface normals are used for calculating the final image using similar algorithms to those employed for polygon rendering. An intermediate technique of this sort was used to produce the image depicted in Fig. 2. This technique has been used on the Transputer based Medical Graphics Workstation developed at University College London in the 1980's which has been in clinical use since its completion (Tan et al., 1991).

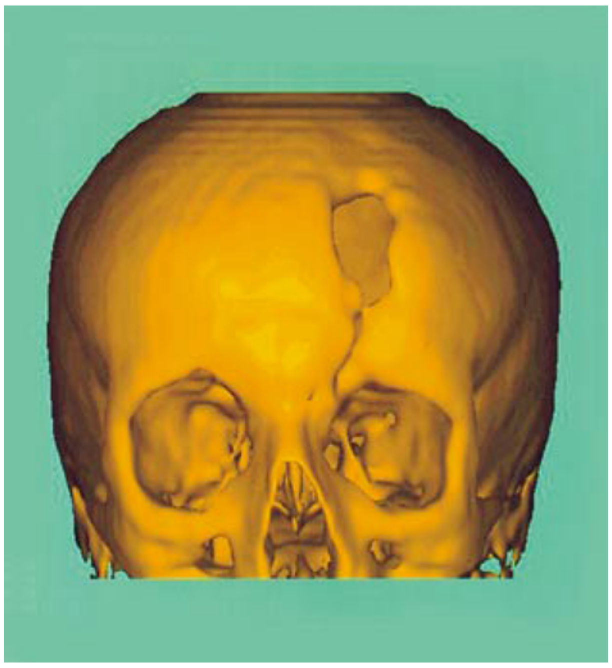
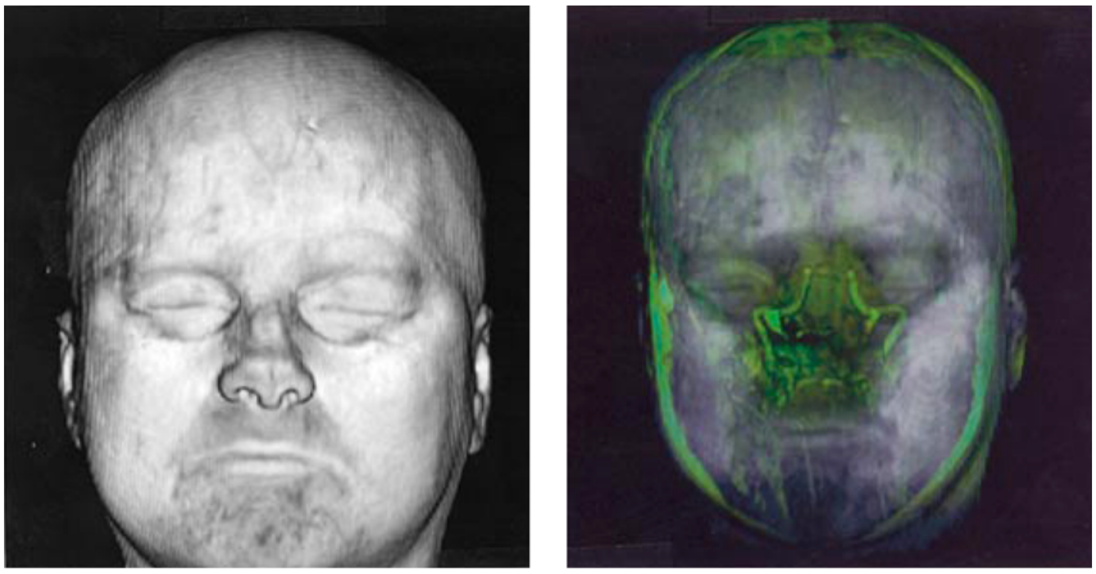


Fig. 2. An intermediate technique of calculating surface normals has been used to produce this image from a set of CT scans of a patient with a skull defect.

2.2 Volume Rendering

Another method commonly used for the visualization of 3D medical image data is known as 'volume rendering' (Levoy, 1988; Drebin et al., 1988). This visualization technique works by projecting each voxel onto a viewing plane with a value related to the physical property represented in the voxel array. For example, a voxel containing bone with a high X-ray absorption coefficient might be projected with a high value. The most advanced systems allow the operator to interactively construct a look-up table relating the physical value associated with the voxel to the value it contributes to the image at the chosen viewing plane. A pixel in the viewing plane will usually receive contributions from many voxels and the operator may control the manner in which these contributions are composited. For example, the operator may choose to display only the maximum contribution from any voxel along a ray. This produces an image known as the maximum intensity projection (MIP). On the other hand any individual voxel associated value may be assigned a maximum opacity value to produce the same images as would be produced by surface rendering.

Figures 3(a) and 3(b) show two volume rendered images with different look up tables which demonstrate how different anatomical structures may be made visible through others which are being rendered transparent. Major blood vessels may, for example, be effectively rendered visible within the anatomical volume as in Fig. 3(b).



(a) (b)

Fig. 3. Volume rendered images using different look up tables demonstrating how hidden anatomical structures can be made visible through others. In 3(b) the major blood vessels are rendered visible.

Generally, a volume rendered image appears different from that of a surface rendered image in that anatomical structures are presented as having some degree of transparency. For some clinical procedures such as image-guided biopsy or trans-cutaneous thermal ablation, transparency may greatly enhance depth perception and thus increase the accuracy of the procedure. It is apparent that surfaces are not explicitly rendered, but human perception reconstructs structures that are perceived in the correct spatial relationship within the anatomy.

The transparency which volume rendering offers also enables the placement of surgical instruments within 3D structures with great accuracy (Jolesz and Kikinis, 1995).

Until recently, volume rendering was considered to be inherently slow due to the large voxel data sets which had to be processed for each new view of the anatomy. However, the development of new ideas and algorithms for volume rendering using texture mapping hardware architectures has removed this obstacle (Cabral et al., 1995). Volume rendered image update is now possible at speeds that meet the requirements of image guided surgery, the most demanding clinical application in terms of speed. Moreover, there are systems now available, which allow rendering techniques to be mixed and the results presented on the same screen in a clinically advantageous manner (Englmeier et al., 1997). The human anatomy may be represented as a voxel set and volume rendered, whilst surgical tools are more conveniently rendered from polygon surface models. The Silicon Graphics system we are currently using permits this hybrid rendering of multidimensional image data.

The hardware accelerated graphics techniques apply to polygon rendering as well as to volume rendering. An implementation of OpenGL libraries and routines has made the programming much easier and faster to develop. The OpenGL library has now become a standard adopted by most hardware manufacturers, therefore code may be ported from one system to another with little effort.

3. Presentation of the Rendered Images

The method chosen for the presentation of the rendered images depends on the application. There are a number of methods that have been described:

3.1 Two-dimensional Displays

Most of the clinical applications reported present the images of the rendered three dimensional anatomy on a single video screen. This is two dimensional, and thus the rendering requires additional depth cues to enable the viewer to appreciate the three dimensional character of the data. This is usually achieved in a satisfactory manner by carefully selecting the surface illumination model and using such devices as a component of depth shading where objects further from the viewer are more weakly illuminated. Thus, two bone surfaces which are at different distances from a viewer, but have the same orientation to both light source and viewer position will non-the-less be rendered with a different intensity on the video screen. If the images are dynamic, the anatomical object can be shown in rotation, adding viewing parallax to the depth cues. Perspective may also be used as an additional depth cue.

3.2 Stereoscopic Presentations

These presentations require the rendering of two images with a disparity corresponding to the binocular disparity which would be expected for viewing the object at a chosen distance in real life. The two images may be presented on a single video screen and viewed from a suitable distance to give the impression of seeing a single three-dimensional object. Various aids to enable correct left and right eye viewing may also be used. These include polarised screens and glasses or shutter goggles. The two images may also be transmitted through two separate eyepieces appearing as if they were viewed through a binocular microscope for example. The single perceptually fused image has the appearance of a real three-dimensional object. This kind of presentation is suitable for the use of virtual and augmented reality in clinical applications that will be described later in this paper. Stereoscopic images may also be similarly delivered to each eye by display on small Liquid Crystal Display (LCD) arrays placed close to the eyes in a head mounted display.

Some methods of image presentation project light via LCD arrays or video systems into each eye of the observer to simulate binocular parallax so that the visualised data appears to be floating in the viewing space. In this form it is amenable to direct 3D physical measurement (Ezra 1996; Iwata 1995; Hattori 1995; Kameyama et al., 1995; Gautsch et al., 1994). An important aspect of this kind of display is that the viewer is unencumbered as is the case with using a head mounted display, and does not have to adopt a tiring posture.

4. User Interfaces and Data Structures

The use of data visualization in medicine has been growing over the past twenty years in many different centres world wide. This has led to a wide variety of different user interfaces, data structures and formats. Clearly, some uniformity is likely to lead to more rapid development and greater safety.

The requirements of the user interface for data visualization in clinical applications are usually demanding. The user must be provided with methods of interactively controlling rendering look up tables. This is often facilitated by provision of a visual tool since there are many parameters that the user may choose to adjust. Viewpoint must be selectable, and facilities must be provided for making such measurements as length, angle and volume. The user must also be allowed to interact directly with the volume data sets so as to simulate dissection and surgical procedures. There is no standard for the user interfaces in 3D medical graphics applications, although we have reached a stage where this is urgently needed. This is because of the large number of peripheral interface manufacturers who have created a large variety of user interfaces. Attempts have also been made to standardise 2D and 3D data formats. The introduction of the Internet is accelerating moves towards standardisation.

5. Which Visualization Techniques Are Most Appropriate?

In deciding which visualization technique to use, many factors come into play. The clinical purpose for which the data is to be used is the most significant. The full voxel data set must generally be maintained if surgery is to be simulated on individual patient tissues consisting of several types.

As in many visualization applications, speed of rendering is important. For the pioneers of visualization in medicine, the limitation of processor speed was frustrating, since surgeons attempting to simulate surgery were seldom happy to wait overnight to see the results of their manipulations. For simulation to come into effective use, the visualization of manipulated data sets needed to be 'interactive'. More than a few seconds delay in seeing the effect of an action was regarded as unsatisfactory for the majority of clinical applications. For image guided surgery, the demand for speed is even greater, since it could be dangerous for the images presented during surgery to lag too far behind the real world situation. The meaning of the term "interactive rate" depends on the application. 1 Hz is sufficient for some applications such as surgical planning but it would be totally inadequate for per-operative surgical navigation.

With access to sufficient computing power and computer memory, volume rendering techniques will meet all requirements. In particular, the recent introduction of hardware acceleration using texture mapping and the OpenGL graphics interface has made it possible to deliver an updated image at a rate of approximately 20 per second for a typical voxel data set. We have used this technique of visualization in most of the examples in this paper.

Irrespective of the clinical problem, there will also be various budgetary constraints to consider. We have developed systems for visualization on parallel processing systems, PCs and are currently using top of the range Silicon Graphics hardware. The first two systems are relatively cheap and offer a considerable functionality allowing visualization and surgical simulation, but not in real time. By real time, we mean the rate at which a sequence of changing images must be presented in order for a viewer to not be able to sense the discontinuities between individual frames. For the images we deal with, this is a rate of approximately 20 frames per second per eye. This is clearly more difficult to achieve and instead a rate of 10 Hz is considered to be a rate suitable for surgical navigation. The Silicon Graphics system that we are currently using (Onyx2 Infinite Reality) is capable of updating a view of the anatomy of the head at this rate, this being a requirement for the dynamic use of augmented reality in image guided surgery.

For some time the desire for photo-realistic images and interactivity appeared to create a contradiction, but this is gradually being removed by better algorithms and computer hardware developments.

6. Clinical Applications

Clinical applications of 3D data visualization include elements of one or more of the following: surgical simulation, planning and live navigation, enhanced diagnosis, radiotherapy treatment planning and modelling.

6.1 Simulated Dissection for Surgical Simulation, Planning and Implant Design

(a) Maxillofacial Surgery

Among the earliest reports on the clinical use of 3D data visualization were applications in craniofacial surgery. CT data was ideal for imaging bone and had a spatial accuracy that was acceptable. There is also in this specialisation a great need for careful preoperative planning since the effect of surgery will be both functional and aesthetic. The surgery was also mostly of a non-urgent nature, so the visualization hardware of the day could satisfy the time requirements for a surgical plan. Vannier, Marsh and Warren concluded in their pioneering paper of 1983 (Vannier et al., 1983) that 3D images were helpful for instructing physicians and even patients themselves in pathological anatomy and craniofacial surgical procedures. Later, surgical simulation systems (Cutting et al., 1986) and interactive workstations (Fujioka et al., 1988; Moss et al., 1988; Tan et al., 1991) were developed with functions that specifically addressed the problems of simulating, rehearsing and planning craniofacial surgery interactively. At least one of these early systems incorporated an automated optimisation program which computed the postoperative positions of bone fragments resulting from interactive osteotomies which best fitted the appropriate normal cephalometric form (Cutting et al., 1986). Some of these systems also produced images of data that modelled the predicted outcome of surgery using interpolated empirical data (Fujioka et al., 1988; Moss et al., 1988). The predicted post-surgical face could be displayed from any viewpoint. Techniques were also developed to use visualization to accurately compare pre- and post operative facial shape in three dimensions and to visualise subsequent changes over extended periods of time. Fast methods for registering the three-dimensional data sets were developed for this purpose (Fright and Linney, 1993). The latest systems use physical models of tissue behaviour to provide accurate predictions of post-surgical facial appearance (Keeve et al., 1996). Clinical assessments have demonstrated the superiority of computer based visualization over other methods in craniofacial and orthopaedic diagnosis (Vannier et al., 1989) and the application of these methods to craniofacial surgery has now been thoroughly validated (Patel et al., 1996).

(b) Orthopaedic Surgery

The planning of orthopaedic surgery has similar requirements to those of maxillofacial surgery. The shapes of individual bones need to be visualized and decisions made on the treatment necessary to establish normality. As individual prostheses and implants also need to be designed, a considerable element of CAD-CAM (Computer Aided Design-Computer Aided Manufacture) is used along with or integrated with the visualization systems (Sutherland et al., 1994). Image guided robots (Kienzle et al., 1996) are also beginning to emerge as a possible means of precision surgery. Data visualization techniques have been applied to hip, pelvic bone, knee and vertebral column surgery.

(c) Customised Surgical Models, Prostheses and Implant Design

The visualization of 3D data sets representing the human anatomy has opened up the possibility of using numerically controlled milling machines and stereolithographic systems to produce prostheses and alloplastic implants customised to the individual patient to provide a near perfect fit to their anatomy. Life size surgical models of the individual patient anatomy have also been found to be useful for treatment planning purposes (Lambrecht et al., 1995; Nakajima et al., 1995). It has been found that such models allow a higher precision to be achieved than traditional articulators when transferring maxillofacial surgical plans to patients, especially those with asymmetries (Fuhrmann et al., 1994). Templates customised to the patient's anatomy have also been constructed for the guidance of surgical tools and the placement of prostheses.

Titanium plates to replace defects in the skull which have been designed directly from visualised CT derived surface data have been shown to fit the patient exceptionally well. The results of a clinical assessment showed that the plates produced excellent aesthetic results, and the time for the operation to insert the plates was considerably reduced since no manual adaptation of the plate to the defect was usually required (Joffe et al., 1992). Similarly soft tissue defects due to muscle wasting have been successfully corrected with implants designed using anatomical visualization based on optical surface scan data. The technique involves mirror imaging the normal side of the body to determine the implant size and shape required to restore the shape and size of the defective side (Linney et al., 1997).

Figures 4(a) and 4(b) illustrate the simulation of surgery on bone to isolate and examine a cranial defect and Figure 4(c) shows the interactive placing of markers for the measurement of the dimensions of the defect and the thickness of the surrounding skull. Figure 5 shows a surgical model that has been automatically milled in dense polyurethane using surface co-ordinates derived from the data visualized in Fig. 2. This model was subsequently used to design an accurately fitting titanium plate to close the defect in the patient's skull.

Reports have indicated that in these surgical areas, the operations have been thoroughly planned, different strategies have been studied for optimal choice, greater accuracy has been achieved and there has been a reduction in surgical operating time. The techniques described are gradually being extended in application to all parts of the body.

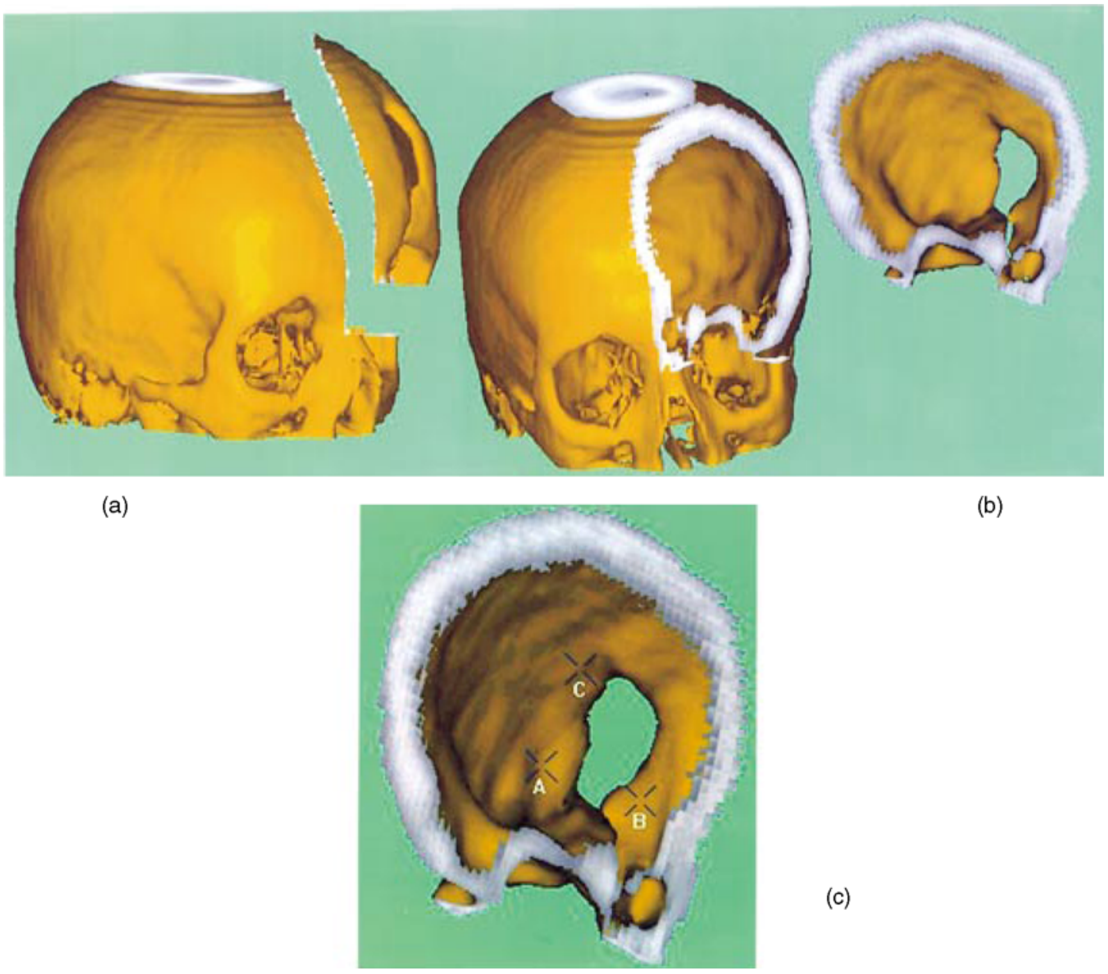


Fig. 4. (a) and (b) show the simulated removal of the defective segment of a patient's skull to enable detailed interactive measurements as illustrated in (c).

Fig. 5. The surgical model made by using computer derived surface co-ordinates from the data visualised in Fig. 2 to drive a numerically controlled milling machine.

6.2 Enhanced Diagnosis

The ability to use data visualization to dissect the virtual patient and explore their anatomy clearly offers a considerable diagnostic advantage. Any part of the anatomy may be isolated and examined in detail. In orthopaedics, this facility has for example been used to analyze complex fractures (Gautsch et al., 1994). Various thresholds may be applied to visualize certain voxel values. For diagnosis, the voxel value ranges of the 3D data do not necessarily coincide with the volumes of anatomical structures. They may for example correspond to regions of similar functionality or biomechanical properties. Data visualization permits certain properties of tissue that are not normally visible to be seen. Volume rendering thus has the potential to completely surpass direct inspection. The velocity of blood flow (Lyden and Nelson, 1997), the strength of bones or the metabolic rate as evidenced by the concentration of a radioactive substance may all be visualized using volume rendering techniques. Combining function and form into a single three-dimensional presentation by image or data fusion has the potential to improve both understanding and localisation of pathology.

Fusing images or data requires spatial and in some cases temporal registration of data sets (Lavallee et al., 1995). An early example of 3D data set registration used data from CT and MRI for anatomy with PET data sets to show function (Pelizzari et al., 1989).

Figure 6 shows the fusion of CT and MRI data sets such that both the vertebra and soft tissues may be examined in their correct relationship in a single image. The fused data sets have been volume rendered so that all tissues have some transparency. The subject was a young female. The surface anatomy of the chest and abdomen may be seen as well as internal anatomy.

Fig. 6. CT and MRI data sets have been registered and fused so that both bone and soft tissue may be examined in their correct relationship in a single image.

6.3. Fetal Imaging

The reconstruction and visualization of 3D data sets from ultrasound has permitted the detailed examination of fetal development. For example, Deng et al. (1996) report on the reconstruction of the fetal heart as well as on dynamic studies, with gated ultrasound, on its function. Figure 7 shows typical images of a fetus from two viewpoints rendered from a 3D-ultrasound data set. The face, which is difficult to assess from 2D scans can be clearly seen.

Fig. 7. An image of a 3D data set of a living fetus collected using a tracked ultrasound probe.

6.4 Interventional Radiology and Image Guided Surgery

Image guided surgery and interventional radiology have a long history. The very earliest 3D example being reported as early as 1898 (Davidson, 1898). In stereotactic surgery, images have, for a long time, been used to compute safe trajectories to the accurate location of targets within the anatomy. These techniques has evolved and undergone assessment over more than 20 years (Mueller et al., 1988; Lunsford et al., 1990) with gradual improvements in medical imaging, visualization techniques, computer graphics and spatial tracking.

The use of image guidance has resulted in reduced invasiveness, improved localisation and targeting, along with simultaneous planning and optimization of trajectories to avoid damaging vital structures, for biopsies or percutaneous thermal/laser ablation for example.

In recent years technological advances have made it possible to use 3D visualization for surgical guidance by simultaneously using data from many sources. Some of the most complex multi-modality systems are those associated with neurosurgery. Peters et al. (1994) describe the combination of stereoscopic Digital Subtraction Angiography (DSA) and 3D (MRI) for image-guided neurosurgery. The stereoscopic visualization also included the position and orientation of a tracked hand held probe. The progress of the intervention could thus be viewed on a screen as it took place. The fusion of the patient's vascular and anatomical data in this way gave the surgeon a complete picture of brain structures through which he was passing electrode-guiding cannulas, allowing him to avoid critical vessels en route to the targets.

Iseki et al. (1995) report on the combination of pre-operative 3D MRI, CT, and SPECT with intraoperative ultrasound data plus high definition video images of DSA all combined into a single system for computer assisted neurosurgery (Iseki et al., 1995). Accuracy of placement of hand held probes using multimodality data has been reported to be within a 1mm cube in some systems (Grönemeyer and Seibel, 1996).

The size of surgical wounds correlates directly with the length of stay in hospital as well as morbidity. One way in which surgeons have sought to improve surgery is by moving towards minimum access surgery, thus decreasing the size of wounds. To reduce risk and improve outcome, surgical strategies have implemented newer technology such as endoscopy to enable adequate visualisation of the hidden surgical field. For image guided surgery, the use of virtual and augmented reality offers a realistic opportunity to make these methods both safe and effective. These techniques however, require real time update of stereoscopic images. By allowing the real and virtual worlds to be registered and presented in a single field of view, these systems provide the surgeon with what amounts to X-ray vision, enabling structures within the patient to be seen prior to, and during surgery. Images of the surgical tools as they cut and penetrate tissues can also be included. Complementary information may be viewed simultaneously but the surgeon is not immersed in a virtual world, as is the case with virtual environments. Some large-scale projects are underway (Carlson, 1996).

The delivery of the images through head mounted display units has been proposed by a number of groups, but these are currently cumbersome and do not have a high resolution. As many of the applications are for surgery that normally uses stereoscopic optical microscopes, this would seem to be an ideal method of delivery of images for augmented reality in a totally unobtrusive way. The development and use of a system based on this idea was described more than ten years ago (Roberts et al., 1986).

Augmented reality offers a simple and secure approach to the question of registration of the patient with the other entities involved in image guided surgery. Since the real and virtual worlds may be mixed, it is possible to view the anatomical surface of the patient, which might be the skin surface or exposed bone together with a virtual image of the same anatomy. Parameters may then the adjusted to bring surfaces into coincidence visually, providing for a registration in which the practitioner would place a high degree of confidence. Several reports have appeared on the successful use of such a method (Gleason et al., 1994; Taren et al., 1995; Kall et al., 1996).

Figure 8 shows an image of a surgical tool with spherical cutter (depicted in yellow) that is being tracked by ultrasound together with a visualization of a patient's skull. The cut in the temporal bone has been made by the operator using the tool. This system can be used for both rehearsing surgery as well as for navigation and guidance of tools within the patient's anatomy during surgery.

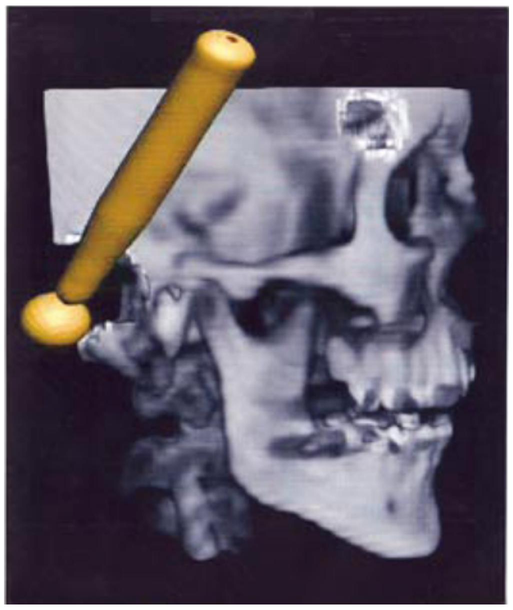


Fig. 8. A hand held surgical tool is tracked by ultrasound and is shown cutting into the temporal bone of a patient's skull. This system can be used for both rehearsing surgery or for intra operative image-guided navigation.

Recently per operative systems have emerged which collect 3D data live during surgical operations. These data need to be displayed at high speed to be effective, and presented in some way along with the real patient. Developments on systems of this sort have been described using ultrasound and MRI data. The ultrasound system uses volume rendering and aims to update images in real time which are then presented in an augmented reality mode so that the visualized ultrasound data set can be seen as if it was inside the patient (Bajura et al., 1992).

Schenk et al. (1995) report on the use of a super-conducting open-configuration MR imaging system for image-guided therapy. The open magnet MRI system has a positional accuracy of 1.00 mm (standard deviation .5 mm), but this still requires a second or more to update the fastest images. If data from such systems could be displayed by stereoscopic visualization image delivery systems, the real time changes occurring within tissue during surgical procedures such as thermal ablation could be seen.

6.5 Telesurgery and Diagnostics

The concept of the virtual patient has opened up the possibility of diagnosis, treatment planning or surgery being performed remotely. An experienced radiologist or even a team of radiologists distributed over a wide geographical area can now examine the virtual patient to decide on a diagnosis. A highly skilled surgeon may operate on the virtual patient with a robot replicating their actions in relation to the real patient at a remote site. Surgeons may also jointly plan treatment at widespread sites by distribution of the patient data to these sites using computer networks such as the World Wide Web. There are some very large scale projects currently aimed at turning these concepts into a reality (Carlson, 1996).

6.6 Radiotherapy Planning

Interestingly, radiotherapy treatment planning was probably the first field using registration of real and virtual worlds on a regular basis. The aim is to deliver the maximum uniform radiation dose to a tumour whilst avoiding, as far as possible, the irradiation of healthy tissues. Data visualization has the potential to enable treatment plans to be developed which are optimised in three dimensions. Radiotherapy dose distributions are calculated from the disposition of the sources of ionising radiation with respect to the patient's body and may be represented in three dimensions by isodose surfaces. These may then be displayed along with the patient's anatomy. A clinician may select volumes to be irradiated and those to be spared, and both interactive human and computer optimisation may be carried out (Schmidt et al., 1994; Kalet et al., 1996). It has been reported that the doses can be calculated and displayed along with the anatomy in real time making it easy to explore a variety of treatment strategies (Matthews et al., 1996). Several systems have been reported which are successfully using these methods.

6.7 Modelling the Human Body

There are many endeavours currently aimed at modelling the human body, anatomically, kinematically and functionally. The output of a model is most often numeric in form, data perhaps representing a shape, a movement or some metabolic or electrical activity.

3D computer graphics and visualization systems are being developed to provide a high degree of visual realism for dynamic models of the human musculoskeletal system (Chao et al., 1993). The biomechanical behaviour of entirely soft tissue systems is also being simulated and visualised with great realism (Suzuki et al., 1993)

6.8 Training, Teaching and Learning

The 3D visualization of the human body and its functions provides excellent teaching material of both normal and abnormal states. The information can be delivered as static or dynamic images together with text and oral presentations. It is also possible to include aids to diagnosis and to propose various treatment strategies. With Multi- and Hypermedia it is possible to make all of this information available at low cost either via computer

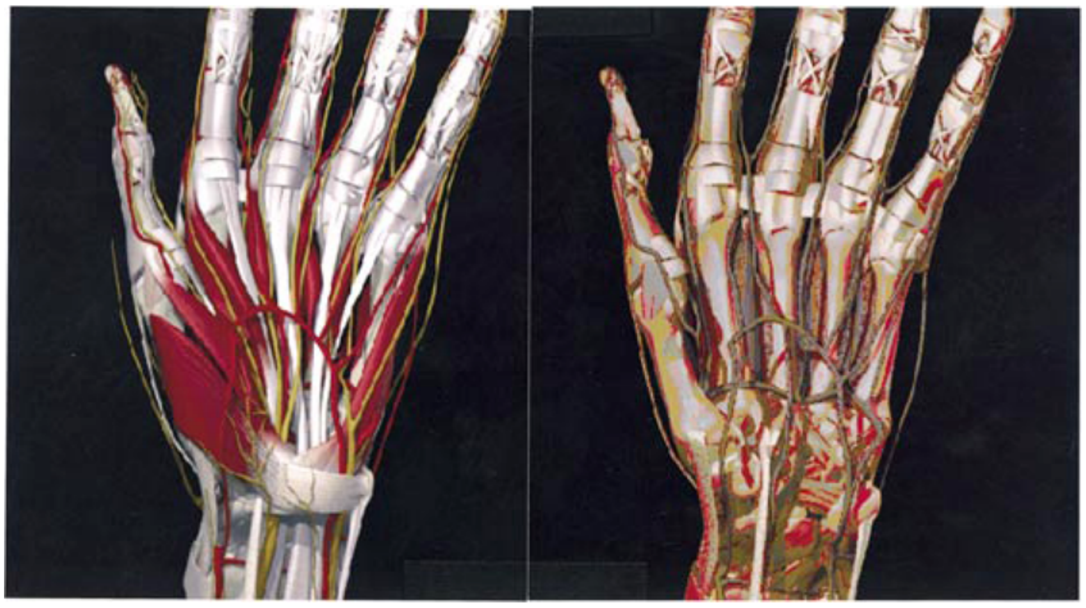


Fig. 9. Two images of the hand captured from the training CD-ROM entitled 'The Interactive Hand' (produced by kind permission of Primal Pictures Ltd).

networks (Chen et al., 1996) or in the form of CD-ROMS. The images produced interactively on the computer screen can be of very high quality and superior to textbook versions that are constrained to the two-dimensional format. Figure 9 shows some typical pictures from a recent CD-ROM entitled 'The Interactive Hand' which is the result of a collaboration between University College London and a multimedia company, Primal Pictures of London. An interactive three-dimensional anatomical atlas has also been reported which allows simulated dissection to be carried out (Schubert et al., 1993). The storage of information and rapid retrieval and display mechanisms have a tremendous advantage in that rare materials will become widely available for teaching, training and diagnostic decision making. At University College London, we have also established a Virtual Medical Laboratory that allows interactive access over the Internet to an archive of rare anatomical material.

7. Economics, Social, Ethical and Legal Issues

With the intense activities directed towards the clinical uses of data visualization some authors are giving consideration to broader issues (Rhodes, 1997); does the use of these new technologies have any legal implications? Who is ultimately responsible for the validity of data after the processes of collection transmission and visualization? Which agency should be monitoring these developments? In some cases, government agencies are recognising the impact of the new technologies. Legal and social issues are taking form in Food and Drug Administration (FDA) guidance. For example, the FDA Centre for Devices and Radiological Health has launched a programme to prepare guidelines on software used in devices for computer aided diagnosis (SCAR News, 1996). Other committees are laying down standards for image guided interventions (Cardella et al., 1996). Some consideration is also being given to the ergonomics and practicalities of using very complex systems in the operating theatre and for robotics and telesurgery from both the patient's point of view and that of the diagnostician or therapist (Rau et al., 1996).

It has already been recognised that there is a need for a uniform image format. This has been agreed after much debate and standards such as DICOM have evolved to meet the requirements of Internet accessible data.

Certainly one effect which visualization has brought about is that where it is used, clinical specialities such as Surgery and Radiology are coming much closer together and a higher degree of communication has been enabled. As the images are now more immediate and obvious, patients are becoming more involved and better informed.

8. Discussion

It has become apparent over the last few years, that there is an exponential increase in the speed of processors and an equivalent decrease in cost of manufacturing. This has opened up an enormous opportunity for all processor intensive applications, including medical graphics. Surgical simulation and planning applications will continue to improve, and higher rates of display will be achieved. A major part of this increase is attributable to the implementation of Open GL in computer graphics. The word interactive has been used to imply speeds of update ranging from 1 frame per second up to 25 frames per second or more. Although this depends on the application, it seems logical to presume that faster frame updates make these applications more "interactive".

The real beneficiaries from improvements in medical graphics applications are patients. Surgical procedures will be made faster, more accurate and graphics will improve relay of information to patients and hence a truly "informed consent".

The cost of new applications is always used to down play or criticise these technologies. However, it is too early to speculate about real costs as these will not be obvious until clinical trials have been performed.

One of the most exciting possibilities for the future will be the development of new surgical techniques that will only become feasible as a result of real time imaging.

We conclude that volume rendering using hardware acceleration and openGL is the way forward for the foreseeable future and will satisfy most of our requirements. We believe that the use of data visualization in clinical applications will continue to grow and demonstrate greater advantages in many fields. In spite of the technology always lagging being human aspirations we are non-the-less seeing dreams steadily becoming realities.

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