3-D Conformal and IMRT: Physics & Clinical Applications
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— CHAPTER 5 —

Image Segmentation and Volume Display for 3-D Treatment planning

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I. INTRODUCTION

A. Uses of 3-D Image Information of 3-D in Treatment Planning

There are several important uses of 3-D anatomical information in radiation treatment planning. Appropriate ways in which this 3-D information is extracted from the underlying tomographic image data, and for its analysis, vary depending on the use to be made of the information. It is instructive to consider what sort of preprocessing and visualization methods are appropriate for the various stages of the RTP process. For some purposes, simple line drawings of contours or projections of segmented structures are sufficient. In other cases, a more elaborate 3-D style of display based on viewing geometric models of objects identified in the image dataset is useful. For many analysis tasks, a 3-D geometric definition of the volume of a particular structure is needed. For some types of objects and/or visualization tasks, a direct visualization of the image data themselves rather than objects segmented and modeled from the data is useful. Here we will discuss the differences between these styles of visualization and attempt to put them in perspective in the context of RTP. For a through discussion of 3-D display methods, see the excellent chapter by Udupa (Udupa 1991).

The planning and delivery of radiation therapy divide naturally into several phases. Initially, the volume within the patient to be treated and not to be treated is identified. This involves first of all, the identification of palpable or visible tumor. In addition, an estimation is made on the basis of clinical information, image data and knowledge of the particular disease in question, of areas of potential microscopic spread of disease which must also be treated. Definition of these volumes typically involves manual or automated segmentation from 3-D image datasets such as CT and MRI either alone or used in combination (Kessler 1991, Phillips 1991, Thornton 1992), together with estimates of subclinical spread, regional involvement and position uncertainties. Functional information, for example from nuclear medicine images (Schad 1987, Kramer 1991, Scott 1994) has also been found helpful in defining areas of viable tumor, which may sometimes be difficult to assess from MRI alone (Holman 1991) .

Given a beam arrangement, possibly chosen largely on geometric grounds, dosimetric analysis is used to choose between rival plans, or to optimize the weighting of doses from a number of beams. Estimates of tumor control and normal tissue complication probabilities (TCP and NTCP) involve weighted integrations of calculated doses over the volume of tumor and normal structures segmented from image data. Obviously, the reliability of these calculations depends on accurate definition of the 3-D regions of integration – that is, definition of the 3-D geometry of the relevant anatomical structures or functional regions. So for this purpose, simply visualizing the structures of interest and their relationships is not sufficient: the boundaries of the region of interest must be known in the same coordinate system in which the dose calculation has been made. Thus a geometric definition of the regions of interest, derived for example from slice-by-slice image segmentation or explicit voxel classification, is essential, and a direct volume visualization method alone is not adequate for this purpose.

II. EARLY EXAMPLES OF VOLUME DISPLAY IN TREATMENT PLANNING

Radiation therapy planning was one of the earliest areas in which use of 3-D image-based anatomical information was applied to clinical problems. The group at Rhode Island Hospital developed radiation treatment planning systems utilizing patient surface and internal structure contours on multiple slices which were digitized from transaxial tomographs and plotted on a monochrome video monitor or on paper, as viewed from the perspective of candidate beam directions (Reinstein 1978). Hardcopy perspective plots from each beam's point of view were used for design of field apertures and blocks. Subsequently, use of an interactive color graphics system replaced monochrome plots, and coupled with a calculation of dose on multiple planes, allowed interactive display of dose on arbitrarily oriented sections through the patient (McShan 1979). Since no CT information in digital form was used, only contours from films, the 3-D display was limited to wireframe models. These authors noted particularly the utility of visualizing anatomical relationships from the perspective of the radiation source for candidate beam directions. This of course is one of the defining characteristics of what have come to be known as "CT-simulation" or "virtual simulation" systems. In the system described by McShan, beam orientation could be controlled via knobs interfaced to the graphics system, presaging the use a decade later of physical or onscreen knobs to control a "virtual simulator". Goitein et al. (Goitein 1983, Goitein 1983) described a 3-D treatment planning system used both for proton and photon planning, which incorporated a number of capabilities that have since become accepted as standards. Delineation of structures directly from CT image data using interactive graphic displays was supported, with sagittal and coronal reformatted images displayed along with the transverse slices to assist in the appreciation of anatomy. The display of structures or DRRs from the perspective of the radiation source was given the name "beam's-eye view" and once again its utility was stressed:

"The source of radiation is a very natural viewpoint from which to gauge anatomic relationships. If the user's eye is hypothetically placed at that point and directed along the central axis of a hypothetical radiation beam, the relative disposition of structures is readily apparent and judgments as to what would and would not be included in the beam can readily be made. If the user is able interactively to move his eye around to all locations accessible to a radiation source, he can explore which directions provide the greatest separation between, say, the target volume and critical normal structures. Beam-shaping apertures can be designed from these vantage points. These advantages have, of course, been appreciated by others." (Goitein 1983)

Separation of the geometric planning part of RTP – beam's-eye view targeting, field aperture design and generation of DRRs – into a "virtual simulator" as a stand-alone application occurred at the University of North Carolina during the mid to late 1980's (Sherouse 1987, Sherouse 1991). Although the "virtual simulator's" capabilities were basically those already shown by McShan, Goitein and others, the concept of a tool for this collection of tasks as an enhanced virtual analog to conventional simulation was highly opportune, and set the stage for the generation of CT-simulator s to come.

III. CLASSES OF 3-D DISPLAY METHODS

What we think of as "3-D display" is in fact the process of projecting 3-D information onto a 2-D space, the surface of a computer display usually, but also a hardcopy device as previously mentioned. Although there are devices which produce true 3-D displays, such as holograms and varifocal mirror displays, they are rarely used in practice, and for all practical purposes "3-D display" can be taken to mean any of a number of methods for representation of 3-D information on normal computer screens. The process of projecting a view of a 3-D dataset onto a 2-D display surface is called *rendering*, just as in architecture a 2-D picture of a building from a particular point of view is termed "a rendering." The 2-D portion of the display onto which a selected portion of the 3-D scene is projected, whether a "live" display or a region on a hardcopy medium, is called the *view - port* in computer graphics parlance. The source of information in our context is of course 3-D medical image data such as CT, MRI, PET, SPECT, and etc. We will confine the discussion here to anatomical modalities, and speak of CT for the most part as representative of any modality. The image data may be thought of as samples of a 3-D field with characteristic values at each point in space; the sampling intervals and volumes are set by the scan parameters, i.e., field of view, number of pixels, slice thickness and spacing. The rectilinear volumes associated with the 3-D samples are called *voxels*. Ordinarily the image data are samples of a scalar field, as there is only one value at each point, such as a CT number. In the case of MR spectroscopy, of multiple echo MRI images on identical planes, or when multiple image datasets have been registered and fused (as discussed elsewhere in this volume), then the image data may have multiple values at each point, thus representing samples of a vector field. Depending on what aspect of the data is visualized, the vector nature of the field may or may not have significance. In any event, the assembly of voxels and their associated field values are called the *image scene*, and their native coordinate system (image rows, columns, slices) the *scene space*. The 3-D display methods with which we are concerned are thus transformations from this scene space to the *view space* of the display viewport.

A. Geometrically Based Surface Rendering

We wish to contrast different methods of rendering information in 3-D anatomical image datasets. At one level, we distinguish between *surface rendering* and *volume rendering*. The distinction here is what information in the data is projected onto the viewport. In surface rendering, the positions of boundaries in the image scene are projected onto the viewport using any of a number of graphic representations. These boundaries (corresponding to anatomical surfaces) may be defined explicitly – manually or with varying levels of automation – in a *segmentation* operation. In an abstract sense, segmentation can be defined as the operation of separating the image scene into sensible parts and labeling the voxels which belong to each part. In radiation therapy planning applications, generally there are two approaches to segmentation: explicit identification of boundaries (contour drawing for example) or else identification of voxel regions which lie inside or outside objects of interest, implicitly defining the boundaries between these regions as the object surfaces. There are a large number of segmentation methods available which implement each of these styles, either identifying boundaries as contours directly or classifying voxel regions into objects whose surfaces are then used. Commercial treatment planning systems typically offer a selection of segmentation tools, implementing both boundary identification methods such as contour drawing or threshold following, and region definition methods such as region growing or other "fill" operations. The result of either type of segmentation is a geometric representation of the desired object boundaries, usually as a list of points in scene space which have been identified as lying on the boundaries. As an indication of the importance of segmentation in treatment planning, and the widespread recognition of the need for better segmentation tools, the NCI Software Tools contract (Kalet 1990) had as one of its goals the development of a segmentation tool. The resulting tool was the Medical

Anatomy Segmentation Kit or MASK (Tracton 1994) which combined a variety of 2-D and 3-D segmentation techniques into a portable program. Research into segmentation techniques for medical applications continues as an active area. A particularly interesting direction involves the computational-vision based shape descriptor techniques recently developed at the University of North Carolina (Fritsch 1997).

The early work described above displayed the surfaces of 3-D objects as stacks of contours. Such displays are still found useful and are widely used; a typical display from the Virtual Simulator in the PlanUNC ("PLUNC") planning software system is shown in Figure 1. Such "ring stack" or "wire loop" visualization conveys the user-defined important features of the 3-D image scene using a minimal amount of on-screen information. Occlusion of structures is also minimized, reducing the need for computation to perform hidden surface removal or transparency. In the early work of McShan and Reinstein, this type of display was natural since the 3-D structure information was in the form of contours digitized from hardcopy.

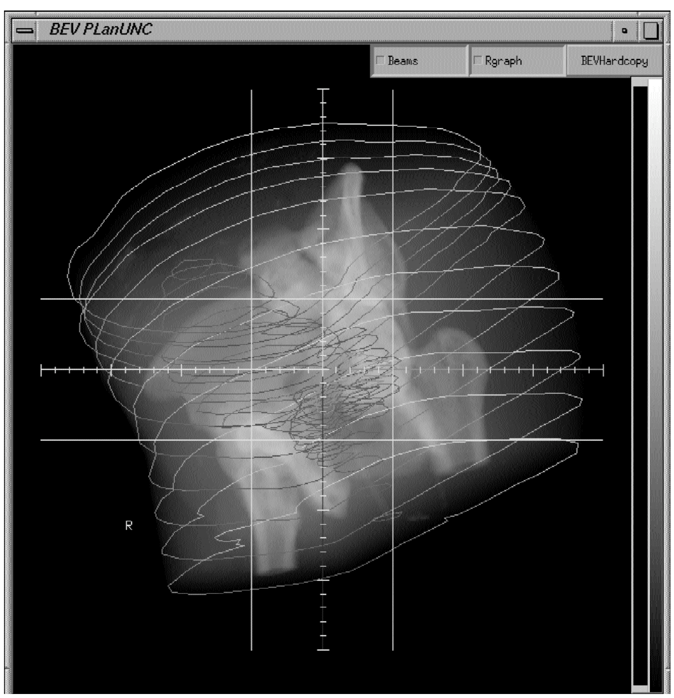

Figure 1. Beam's-eye view (BEV) display from PlanUNC 3-D treatment planning system. External contour, target and normal structures are represented as 3-D wire loops as viewed from the perspective of the radiation source. In this example, a digitally reconstructed radiograph (DRR) is also placed behind the 3-D objects.

More elaborate surface rendered displays using polygonal models of surfaces have also been heavily used in treatment planning systems. An outstanding examples is the system developed at the University of Michigan (Fraass 1987). Since 3-D lines and polygons are an essential component used in computer graphics for many applications, a great deal of effort has gone into development of optimized algorithms for high quality and efficient rendering, shading, hidden surface removal, and etc. for such displays. Furthermore, hardware to directly render scenes composed of these primitives has a long history of development and is readily available at modest cost, for example in personal computers. In our applications, then, line and polygon models can be manipulated rapidly in a high-quality shaded surface display to aid in identification of beam directions which are particularly favorable or unfavorable. Interactivity is always maximized by limiting the complexity of the display, and using such graphic representations the beam's-eye view targeting phase can proceed rapidly. Surface rendering as a visualization technique has the advantage that objects such as isodose surfaces and geometric models of beam boundaries can be included in the rendered view, represented as either opaque or transparent surfaces, and switched on and off with ease using standard computer graphics techniques. An example of such a display from the Radionics "Xknife" radiosurgery planning system is shown in Figure 2.

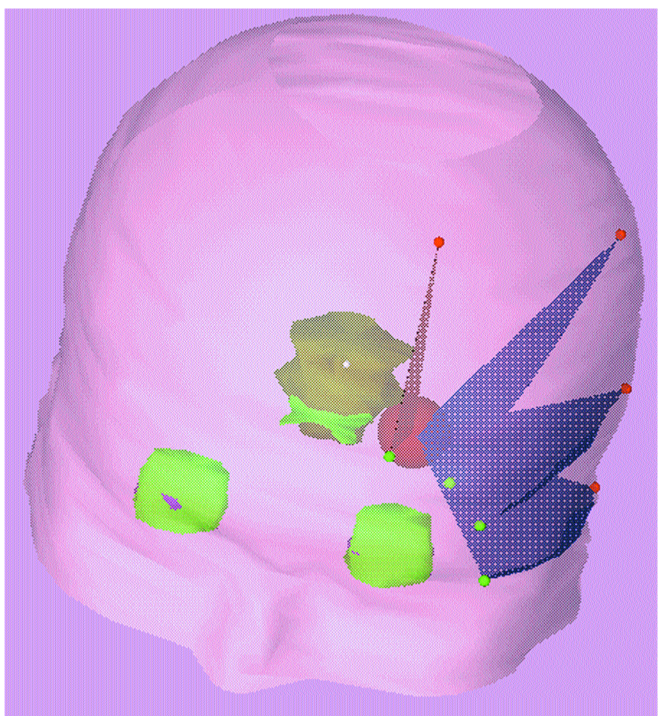

Figure 2. Shaded surface rendering of external surface, target, organs at risk (eyes) and planes of confocal arcs from Radionics "Xknife" radiosurgery planning system.

B. Voxel Based Surface Rendering

Another variant of surface rendering is typified by the General Electric "Advantage Windows" diagnostic workstation and "Advantage Sim" CT-simulator. Rather than representing object boundaries as contours or lists of polyhedral facets connecting vertices, these methods instead render views of the regions of classified voxels themselves, considered as miniature cuboids. Each voxel defined to lie within the right kidney for example, might be rendered onto the viewport with a characteristic visual attribute (colored red, perhaps). Since voxels distant from the viewpoint of the rendering are obscured by those nearer, after all the classified voxels have been projected onto the viewport and rendered, the viewport contains an image of the visible surface of the classified region. Multiple sets of voxels can be rendered into a single view, or course, allowing as many objects as desired to be visualized. Voxels in regions that enclose other regions may be rendered with a transparency attribute, allowing the appearance of "seeing through" skin to internal anatomical objects within for example. Extremely elegant displays may be produced in this way, as has been demonstrated by (Höhne 1996), among others. An example of such a display from the Picker AcQSim CT-simulation system is shown in Figure 3.

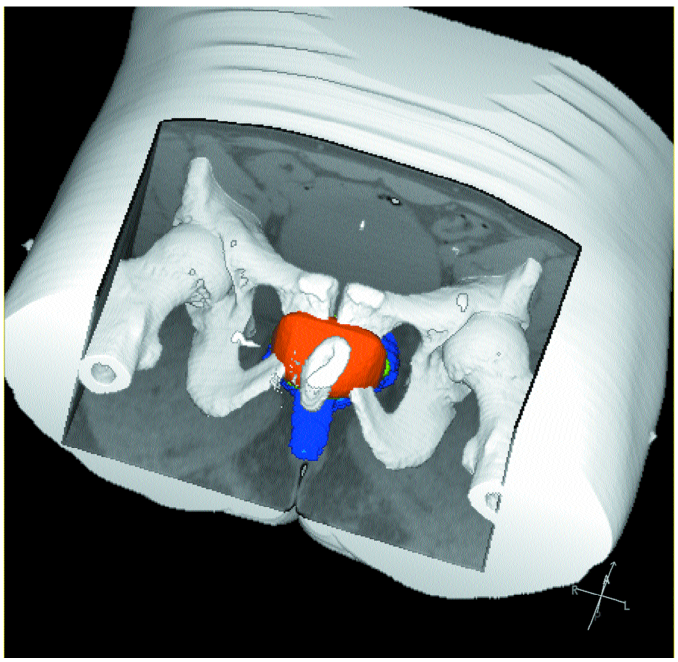

Figure 3. Voxel-based surface rendering of external surface, bones, target and organs at risk from Picker AcQSim CT-simulation system. Cut surfaces are colored with corresponding CT intensity data.

An important feature of any surface rendering method in the context of RTP is that it requires the definition of the surfaces to be rendered. Although obvious, this is important because as mentioned earlier, display is not the only use for 3-D in the RTP process. Display alone can only facilitate the geometric targeting part of RTP, not the dosimetric analysis part, and certainly not the registration of the "virtual patient" of the 3-D plan with the physical patient in the treatment room, which is essential if the actual treatment is to faithfully reproduce that which has been planned. When beam angles, energies, fluence maps, etc. are to be optimized based on dose and not on anatomical coverage alone, the regions of interest over which quantities such as dose-volume histograms (DVH), TCP and NTCP are evaluated must obviously be geometrically defined. Thus, an important consequence of the segmentation step that precedes any surface rendering display method is the definition of the regions required for subsequent optimization or analysis.

C. Volume Rendering

While surface rendering techniques produce views of objects in the image scene based on identified boundaries, volume rendering techniques produce views directly from the image data themselves. Just as in the case of surface rendering, it is necessary to define which parts of the image scene should be visible in the rendered view. In the case of volume rendering however, this classification into fully, partially or not at all visible parts of the scene, and the assignment of visual attributes such as color, is done on a voxel by voxel basis, not as a binary classification ("brain" vs. "eye") but in a probabilistic or "fuzzy" way. Often, this probabilistic classification is not performed as a separate preprocessing step, but "on the fly" as part of the production of a rendered view.

Classification assigns to each voxel a set of visual attributes, such as color and intensity, as well as a property called *opacity* which controls how much the voxel should obscure other voxels which lie beyond it during the calculation of a rendered view. Opacity is the complement of transparency, and is analogous to the linear attenuation coefficient assigned to each voxel in the computation of a digitally reconstructed radiograph (DRR). In fact, the computation of a volume rendered view may be arranged in a way that is altogether highly analogous to the computation of a DRR. Differences are in the meaning of the opacity attribute compared to a linear attenuation coefficient, the use of shading and the accumulation ("*compositing*") of visual attributes in the volume rendering, which is absent from the DRR. In both cases, the voxels in the image scene are assigned an attribute (attenuation or opacity) to control how transparent or opaque they will appear. Voxel attributes are then integrated along rays from the viewpoint to the projection plane to define the final intensity and color of each pixel in the viewport. The rays may diverge if the view incorporates perspective, or they may be parallel if it does not. The similarity of processing in production of DRRs and volume rendered view is exploited by the Picker VoxelQ workstation, part of the AcQSim CT-simulator , which has the ability to compute not only beam's-eye view DRRs but also beam's-eye view volume renderings, using an opacity weighted compositing algorithm quite similar to that used by Drebin and others. This compositing is performed in near real time using proprietary voxel processing hardware in the VoxelQ (Goldwasser 1988) and the renderings are known as "digitally composited radiographs" or DCRs. An example is shown in Figure 4.

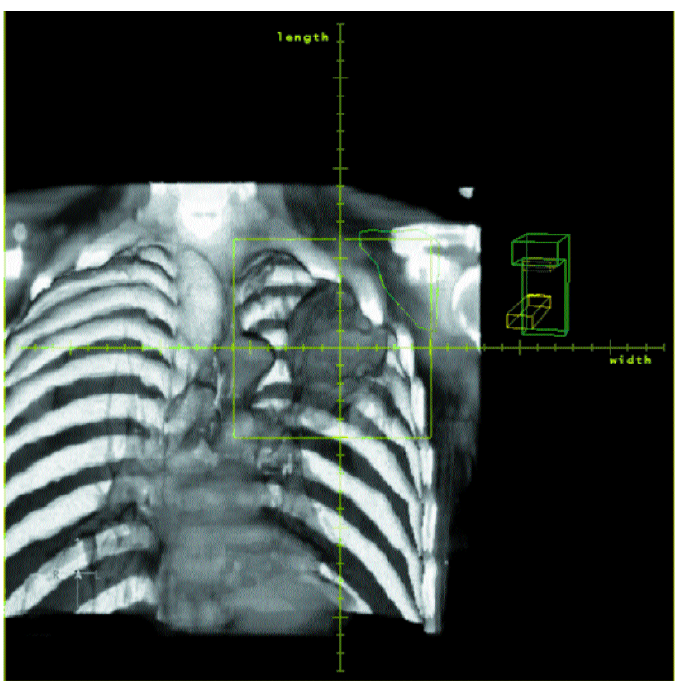

Figure 4. "Digitally composited radiograph" from Picker AcQSim. Cutting plane removes anterior portion of patient; opacity classification renders lung mass visible while suppressing lung parenchyma.

A number of investigators have applied general-purpose volume visualization software to the problem of 3-D RTP (Gehring 1991, Bourland 1992). The visualizations produced by Gehring are particularly elegant, allowing inclusion of geometrically defined objects such as radiation beams and models of segmented structures, along with calculated dose distributions, together with anatomical views directly rendered from voxel data. Two treatment planning systems have been developed based on Gehring's work: the University of Wisconsin Stereotactic Radiosurgery System, and the "Pinnacle" system sold by ADAC. Several groups have investigated the use of direct volume visualization in the virtual radiotherapy simulation process. Until quite recently, the computational demands for interactive visualization from extensive datasets such as those used in RTP have restricted the applicability of these techniques. Early studies using the Pixar Image Computer, which had hardware to accelerate opacity-weighted compositing, and its ChapVolumes volume rendering library (Drebin 1988) were quite successful in diagnostic applications (Fishman 1987, Levin 1989, Levin 1989). Unfortunately, attempts to use the Pixar / ChapVolumes system for RTP were not particularly successful. A demonstration project at the University of North Carolina involved a high-speed network link among a virtual simulation workstation, a dedicated graphics supercomputer for volume rendering and a supercomputer for dose computation (Rosenman 1992). Subsecond rendering times could be achieved with acceptable image quality, though widespread availability of such facilities seems unlikely. However, texture mapping hardware capable of performing this type of rendering at interactive rates is today readily available from workstation vendors such as Silicon Graphics, and beginning to become available for inexpensive mass-market computers. Considerable progress has been made in recent years in reducing the computation time for voxel-based rendering in software, and near-interactive performance (~1 second per view) is in fact possible at the current state of the art (Udupa 1992, Lacroute 1994).

IV. DISCUSSION

Presentation of patient anatomy in 3-D views derived from image data is an important part of radiation therapy planning. For some purposes, segmented models of tumor and normal anatomical structures are needed; for example in the calculation of tumor control and normal tissue complication probabilities by functional integration of dose distributions throughout the relevant volumes. Thus, significant time is spent in the treatment planning process in segmentation of tumor and normal structures from 3-D image datasets. For other purposes, such as choosing beam entrance angles and aperture shapes to minimize irradiation of critical normal structures while fully irradiating target volumes, direct volume visualization without segmentation can be useful. Visualization of complex 3-D anatomical structures, geometric optimization of beams and matching of multiple beam borders can be readily carried out using virtual simulation, in principle based on rendered views calculated directly from the image data without an explicit segmentation step.

An important issue with respect to 3-D visualization techniques as applied in RTP, and more generally in any medical (or other) application, is raised by Zeleznik (Zeleznik 1997). Although we readily perceive 3-D information in rendered views, it is not at all straightforward to assess the correctness of this information, or our perception of it. This is a problem not limited to RTP of course, although our desire for quantifiable accuracy may focus the issue for us. Beyond limited tests with phantoms or other well characterized datasets, understanding these uncertainties requires considerable care in characterization of each step involved in the visualization process. It is important to note that not only volume rendering methods need to be subjected to such scrutiny, but segmentation and surface rendering methods as well.

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