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Joshua Napoli*^a, Sandy Stutsman^a, James C. H. Chu^b, Xing Gong^b, Mark J. Rivard^c, Gene Cardarelli^d, Thomas P. Ryan^a, Gregg E. Favalora^a

^aActuality Medical, Inc, 213 Burlington Road, Suite 105, Bedford, MA USA 01730;

^bRush University Medical Center, Chicago, IL 60612, USA;

^cTufts-New England Medical Center, Boston, MA 02111, USA;

^dRhode Island Hospital / Brown Medical School, Providence, RI 02903, USA

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Radiation therapy planning using a volumetric 3-D display: PerspectaRAD

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^bRush University Medical Center, Chicago, IL 60612, USA;

^cTufts-New England Medical Center, Boston, MA 02111, USA;

^dRhode Island Hospital / Brown Medical School, Providence, RI 02903, USA

ABSTRACT

We describe PerspectaRAD, the first tool for the review and modification of external-beam radiation therapy treatment plans with a volumetric three-dimensional display (Perspecta 1.9, Actuality Medical, Bedford, MA, USA) and a dedicated software application (PerspectaRAD, Actuality Medical). We summarize multi-institution retrospective studies that compare the system's efficacy to the incumbent 2-D display-based workflow. Contributions include: visualizing the treatment plan in a volumetric 3-D display, modifying the beam locations and performing point-and-click measurement in 3-D with a 3-D physical interface, and simultaneously viewing volumetric projections of the native CT data and isodose contours. The plans are synchronized with the hospital treatment planning system, Pinnacle³ (Philips Medical, WI, USA). In the largest of five studies, 33 plans were retrospectively randomized and replanned at three institutions, including 12 brain, 10 lung, and 11 abdomen / pelvis. The PerspectaRAD plan was as good as or better than plans created without PerspectaRAD 70% of the time. Radiation overdose regions were more likely to be obvious inside the target volume than when reviewed in the 2-D display alone. However, the planning time was longer with PerspectaRAD. The data demonstrate that PerspectaRAD facilitates the use of non-coplanar beams and has significant potential to achieve better plan quality in radiation therapy.

Keywords: volumetric, autostereoscopic, medical imaging, radiation oncology, treatment plan, haptic, Perspecta

1. INTRODUCTION

The prevalence of cancer remains a staggering problem. In 2007, there were an estimated 1,444,920 new cases of cancer in the United States¹. The cancer treatment team includes surgeons, radiation oncologists, and medical physicists, and has an array of advanced tools to treat these cancers, including the surgical excision of cancerous tissue and the use of controlled radiation sources to irradiate specific structures. However, decreasing the side effects (*morbidity*) and increasing the survival rates remain difficult challenges for these methods.

Our work pertains to a class of cancer treatment known as *external-beam radiation oncology*, which is described in Section 1.3 below. Most people who are treated for cancer receive external-beam radiation treatment. Creating the required three-dimensional treatment plan is a challenging task using the incumbent workflow that relies on traditional 2-D displays, such as desktop LCDs. Sensing that using advanced visualization techniques could improve these plans, we created a software application, PerspectaRAD, that works with the Perspecta® Spatial 3-D Display, a volumetric display². PerspectaRAD projects volumetric imagery of patient anatomy and the treatment plan, which the clinician can inspect and modify. The benefits of PerspectaRAD were assessed in a series of retrospective clinical studies, one of which was a randomized analysis of 33 plans at three major academic medical centers.

The work described here was performed by and with the support of computer scientists, medical physicists, radiation oncologists, statisticians, and a major medical treatment system manufacturer. Participating organizations included: Actuality Medical, Inc. (Bedford, MA, USA), Rush University Medical Center (Chicago, IL, USA), Tufts-New England Medical Center (NEMC, Boston, MA, USA), Rhode Island Hospital / Brown University (Providence, RI, USA), and Philips Medical Systems (WI, USA).

1.1 Perspecta Spatial 3-D Display and Spatial Visualization Environment Software

This work used two versions of the Perspecta volumetric autostereoscopic display (Actuality Medical, Bedford, MA, USA), which differ primarily in terms of computation speed and form-factor. These are illustrated in Figure 1.

We restrict the description here of Perspecta to a summary, since Perspecta and volumetric displays in general are described elsewhere^{2,3,4}. The volume-filling imagery of volumetric displays is typically visible by the unaided eye within a wide horizontal and vertical field of view. The Perspecta Spatial 3-D Display generates 3-D imagery by projecting a sequence of patterned frames (“slices”) onto a swiftly-rotating omnidirectionally diffuse screen.

Data corresponding to a scene-to-be-rendered from an application such as PerspectaRAD are transmitted from a Windows XP-based host PC over gigabit Ethernet to the graphics-rendering hardware of Perspecta, the Volume Rendering Unit (VRU), using SpatialGL⁵, an application programming interface (API) and communication protocol for spatial graphics operations. The VRU is a single-board x86 PC with an NVIDIA graphics processing unit (GPU) that converts the scene description into a series of $198 \times 2 = 396$ slices of 768×768 pixels and 3 color-bit resolution per slice. (A single volume is composed of 198 slices. The factor of 2 accounts for the so-called front-scan and back-scan overlapping volume projections.) The instantaneous volume is stored in a volume buffer in an embedded Core Rendering Electronics module, which then controls a three-chip light engine based on Texas Instruments (Plano, TX, USA) Digital Light Processing™ technology. The light engine projects approximately 6,000 slices/sec onto the 10” (25 cm)-diameter diffuse screen that rotates at 900 rpm. This generates a 3-D image with a visual refresh rate of 30 Hz.

As described elsewhere⁵, “[t]he Perspecta display interprets the SpatialGL stream and renders digital volumetric images through a combination of CPU and GPU algorithms. ... The software architecture has both client and server components. The client component is called the Spatial Visualization Environment. It exposes the features of SpatialGL in a portable way and provides a compatibility layer for legacy graphics APIs. The server component is the Core Rendering Software. It adapts existing rendering resources for spatial 3-D displays.” High-speed rendering algorithms are executed in the VRU’s GPU. The Perspecta Display (with a VRU) renders approximately 500 12-bit CT slices per second and 5.5 million vertices per second at up to 10 volumes per second.

The Spatial Visualization Environment solves the problem that the application software generally runs on separate hardware from the rendering algorithms⁶. Since off-the-shelf PCs are not yet specialized for Spatial 3-D rendering, the process separation is generally more severe than a trip across the PCI-Express bus. Actuality’s Spatial 3-D system architecture solves the problem by partitioning the system into two execution environments that are bridged with a client/server mechanism. The Spatial 3-D Server combines the features of the particular display with dedicated graphical rendering routines, while the Spatial 3-D Client is dedicated to operating the application software. The server implements SpatialGL, an API and communication protocol for spatial graphical operations. It provides fully programmable shaders compatible with the OpenGL shading language and supports rendering of volumetric tetrahedral meshes through the same API calls as triangle, line, or point rendering. Adoption boundaries are eased by minimizing the size of the API and maximizing its similarity to OpenGL. Legacy applications are supported through a drop-in OpenGL to SpatialGL translation driver.

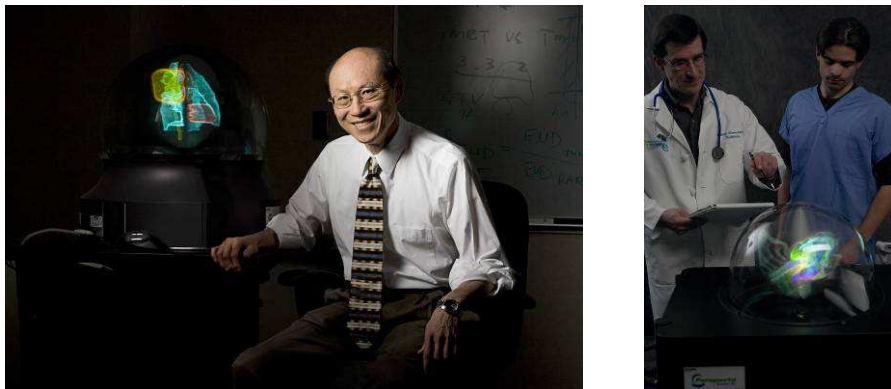


Figure 1: Two versions of the Perspecta Spatial 3-D Display were used in this research. (Left) Co-author (JCHC) with Perspecta 1.7 displaying MATLAB-based radiation therapy planning imagery. *Image credit: Rush University Medical Center Photo Group.* (Right) Perspecta 1.9 has a higher rendering speed and updated form factor.

1.2 Volumetric Displays Enhance Certain Tasks

A volumetric display was chosen since it was hypothesized to provide benefits that best matched the workflows of radiation therapy planning, modification, and validation. The ideal display should be viewable by multiple people at once, provide imagery that can be quickly understood (even by non-specialists such as the patient and family), be amenable to use at the desktop or in the clinician's office, have sufficient image quality, and be compatible with the hospital's radiation therapy planning systems. Volumetric displays satisfy all of these requirements. For example, the Perspecta Display can be used in a darkened office environment, is visible by several simultaneous users with unique viewpoints, creates imagery of sufficient resolution, and can be configured to communicate with the Pinnacle³ (Philips Medical Systems, Wis., USA) planning workstations. Other 3-D architectures, such as stereo displays, would have imposed certain limitations. For example, in the case of stereoscopy, it is costly and unusual to provide egomotion cues to multiple simultaneous clinicians, and obviously requires the use of eyewear. Although stereo headwear has found some acceptance in certain industries, such as petroleum exploration, the clinicians in the studies we describe indicated a strong preference for autostereoscopic displays.

Several studies explore the situations in which volumetric displays excel in various tasks as compared to 2-D and stereoscopic displays. The majority of these studies were performed after 2000, presumably due to the recent availability of volumetric displays with interaction rates and spatial resolutions approaching that of incumbent 2-D displays. In one study, the U.S. Navy determined that the SPAWAR vector-scanned volumetric display excelled at tasks requiring rapid identification of potential airplane collisions⁷. Cardiologists determined that the Perspecta display resulted in significantly faster and more accurate judgment of the spatial orientation of a guidewire within a phantom under ultrasound⁸. However, the study was of limited size. Researchers at the University of Toronto performed several carefully-controlled perceptual studies of volumetric displays^{9,10}. Studies at Purdue University examined the impact of volumetric displays in spatial perception^{11,12}.

1.3 Cancer Treatment via External-Beam Radiation

A software package, PerspectaRAD, was developed to enable the Perspecta Spatial 3-D Display to assist in the review and modification of *external-beam radiation therapy treatment plans* for the treatment of cancer. More than half of the people treated with cancer receive radiation therapy, in which clinicians direct a sequence of high-energy radiation beams through the body to intersect at the tumor. It is critical to strike the tumor and miss the surrounding healthy tissue, but this is challenging and error-prone using a 2-D display alone. For example, in 2-D, the organs are viewed as ~300 slices in parallel planes even though the optimum energy treatment path may be perpendicular or oblique to these planes.

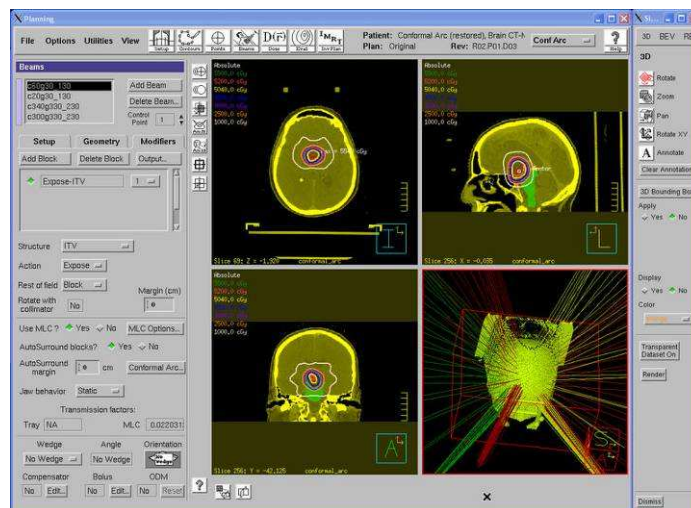


Figure 2: A typical session of radiation therapy planning using Philips Medical's Pinnacle³, a leading treatment planning system. This image depicts a brain tumor radiation plan as a series of 2-D slices and an orthographic 3-D rendering.

The process is described by Chu, et al., as follows¹³:

Radiotherapy treatment planning, a process during which radiation beams are selected to avoid as much critical tissue as possible while delivering high doses to the tumor, is one of the critical steps toward a successful radiation treatment program. Large amounts of detailed patient image and anatomy data are acquired during the treatment planning process. These data may be from CT, MRI, PET, SPECT, or other forms of imaging. Radiation oncologists, medical physicists, and dosimetrists use these data to determine radiation beam orientations and beam shapes for the patient's radiation treatment. Radiation dose distributions are calculated and then superimposed on [the] patient's anatomical structures during evaluation of rival plans. Sophisticated computer algorithms and technologies are used to help manipulate these image and dose data and provide users with the desired three dimensional perspective. Unfortunately, the optimal selection of a set of beams and the efficient choice of the best plan is not trivial even with those technologies. Among the problems impairing the process of beam selection and plan evaluation, one of the most vexing is the desire to visualize the beam and dose coverage three dimensionally while only 2D flat surfaces are used in most current display technologies.

As illustrated in Figure 2, it is particularly difficult and time-consuming to choose beam trajectories that optimally radiate a brain tumor while minimally radiating nearby structures, such as the optic chiasm, spinal cord, and eyes. Traditional 2-D displays force the medical physicist and dosimetrist to mentally "internalize" the three-dimensional locations of the relevant anatomical regions of interest (ROIs) and potential beam trajectories. To build a mental model of the 3-D structure of the plan, the user must repeatedly flip through the slices and memorize the relative locations of the important features. Furthermore, although the planning software provides a variety of 2-D and pseudo-3-D viewing modes, the anatomy is typically displayed as a set of slices perpendicular to the spine (so-called "axial" slices) – but the optimal treatment plan may be non-coplanar to these slices. A true volume-filling display will allow optimal planning because there is no directional bias to the anatomical depiction.

1.4 Contributions

This paper presents several new contributions to the fields of medical imaging, 3-D display, and radiation therapy. To our knowledge this is the first instance of performing radiation therapy planning and evaluation in a volumetric display. The results presented here are due to the first statistically significant study of the applicability of volumetric 3-D to radiation oncology. We note that the results had been presented at various medical conferences in 2006-^{7,13,14,15,16,26,27}. We also describe features and functionality of the first software application dedicated to the volumetric autostereoscopic analysis of radiotherapy treatment plans, PerspectaRAD.

The PerspectaRAD project included a substantial effort to develop and optimize its volumetric user interface. It includes a 3-D pointer input that is both *absolute* and *parkable*. The 3-D pointer is rendered using a glyph that indicates a point and a plane. Also, the user interface can enable and manipulate a volumetric rendering of an oblique "slab" of a medical volume scan. Furthermore, the oblique slab can be overlaid on another volume image (potentially the same volume data as the slab) with an independent color transfer function. The pointer can manipulate a 3-D ruler that also extracts a dose or density profile along its path.

2. PREVIOUS WORK

While we are not aware of previous application of volumetrically-enhanced radiation therapy planning, several researchers have applied various three-dimensional display technologies to medical diagnosis and interventional (i.e. procedural) planning and guidance. Most of these are non-volumetric and are beyond the scope of this article. One survey of medical applications of various 3-D displays is by Owczarczyk and Owczarczyk (1990)¹⁷. Phillips et al. developed a radiation treatment training system using an immersive stereo display that focused on training in setting up the couch and gantry positions¹⁸. While treatment planning also deals with couch and gantry positions, we believe that an immersive environment or a sense of presence is not useful for treatment planning. Instead, our user interface focuses on the effective communication of the hidden aspects of the treatment: the relationship between dose levels and the internal organs of the patient. Efforts to apply haptic interfaces to medical procedure planning or guidance include the PARIS stereoscopic augmented-reality system¹⁹.

Prior to the availability of high-resolution rotating-screen volumetric displays, several research groups investigated the use of varifocal mirror displays^{20,21} in medical imaging, in which a high-speed 2-D display or oscilloscope is re-imaged by a vibrating reflective membrane. For example, at least one group viewed tomographic medical imagery in a varifocal display²². We refer the reader to work performed at the University of North Carolina (UNC) and Duke University that

describes a varifocal 3-D display system in the early 1980s that suggested (but did not implement) applicability to radiation therapy visualization²³. We also refer the reader to work at UNC and North Carolina Memorial Hospital that applied volume rendering (on a 2-D display) to radiation oncology²⁴.

Pointing and picking within a volumetric user interface has been studied by Tovi Grossman at the University of Toronto²⁵. A gesture-based interface was used, where actions were performed literally by pointing with a finger. Gestures were detected using fiducials worn on the fingers and a magnetic or optical tracking system.

As noted in Section 1.4, a section of this paper summarizes our work in volumetric radiotherapy planning, which was reported previously at a variety of medical conferences:

3. PERSPECTARAD SYSTEM IMPLEMENTATION

The PerspectaRAD system augments a traditional treatment planning system with a 3-D user interface presented in a Perspecta Spatial 3-D Display. As an experimental prototype, it was developed to allow medical researchers to determine if the quality of radiation treatment plans would be increased by using a volumetric display. PerspectaRAD helps with *beam placement* and *iterative plan refinement*. An optimal treatment plan is reached with fewer adjustment cycles, because the actual 3-D relationship between the trial plan and the ideal plan can be easily and holistically visualized in Perspecta. PerspectaRAD works on a PC, as a bridge between the Perspecta display and the treatment planning workstation. PerspectaRAD also opens a window on a 2-D screen, where information such as numerical tables and 2-D charts can be more clearly depicted. These are illustrated in Figure 3.

3.1 PerspectaRAD Software Application

The PerspectaRAD software application works in a loosely-coupled mode with the treatment planning workstation. The initial version integrates with the Pinnacle³ from Phillips. PerspectaRAD does not require any change to the workstation, allowing tests of the system to be performed within working clinical environments. PerspectaRAD and Pinnacle³ coordinate through TCP/IP based synchronization messages. A synchronization script is accessible through the Pinnacle³ HostScripts menu. When the script is activated, the treatment plan is synchronized. Further changes in Pinnacle³ are prevented until a signal is given by PerspectaRAD. After the initial synchronization completes, the Perspecta Display shows a 3-D view of the plan. The entire primary image is within Perspecta's dome, and the patient is depicted on their back with feet towards the front-right of Perspecta. After making adjustments in PerspectaRAD, Pinnacle³ can be resynchronized.

Since PerspectaRAD is not FDA-cleared for medical use, safeguards are in place to prevent PerspectaRAD-modified plans from being inadvertently confused with clinical plans. Only trials and objects whose names have been modified with a special suffix can be modified with PerspectaRAD. Also, PerspectaRAD does not directly write to the patient database. All changes can be reviewed within Pinnacle³ before being saved.

Creation of a new radiation treatment plan begins with routine data-entry and setup work. In Pinnacle³, patient identifiers are entered, and CT, MR, and PET datasets are imported and registered as usual. Then the tumors, treatment volumes, and structures at risk are contoured. Once this setup work is complete, the plan is synchronized with PerspectaRAD. Using the 3-D display, the isocenter and beam geometries are configured. Next, the plan is resynchronized with Pinnacle³. Fixed apertures or intensity modulated beams are configured, along with other beam modifiers. Absorbed dose is then calculated in Pinnacle³. Finally, dose objectives are evaluated by the radiation oncologist by evaluating the spatial relationships of the isodose shells in Perspecta and using the dose volume histogram charts in Pinnacle³. The geometry, aperture and evaluation sequence is repeated until further improvement to dose objectives cannot be readily made.

Since user interface design for volumetric displays is not well-developed, a large amount of effort went into the development and refinement of custom user-interface components for PerspectaRAD. The central aspect of the volumetric interface is a 3-D pointer controlled by a Phantom Omni 3-D haptic device (SensAble Technologies, Woburn, MA, U.S.). Many of the aspects of PerspectaRAD are controlled directly by the 3-D pointer. Points of Interest (including the plan's isocenter) and beam direction are set using a point-and-click interface. A 3-D ruler can be defined using the 3-D pointer, which can be used to explore several aspects of the plan. An oblique slab of an image volume can be selected for display using the pointer.

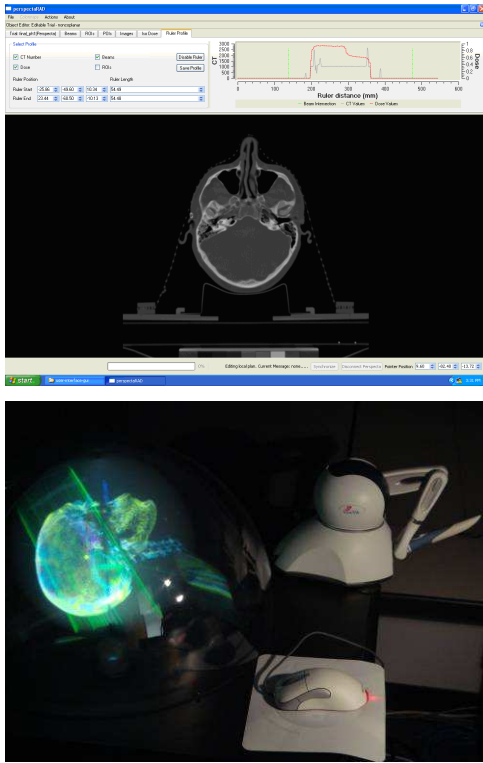


Figure 3: (top) Screen shot of 2-D user interface for PerspectaRAD. This screen shows one 2-D slice of a CT image of a patient's skull. The upper left shows the CT density along a line drawn by the clinician using the 3-D haptic interface. (bottom) The display region of the Perspecta volumetric display, the Phantom haptic interface, and a mouse for scale.

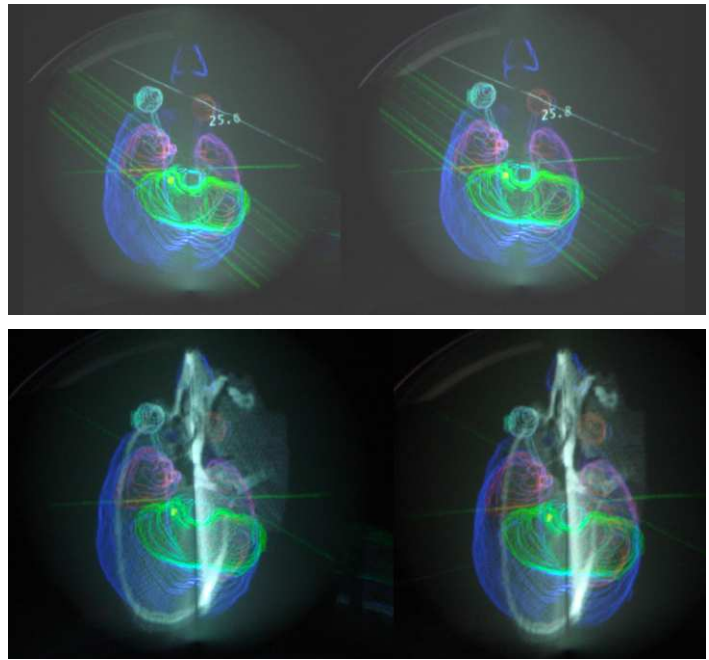


Figure 4: Cross-eye stereo photographs of PerspectaRAD imagery in Perspecta display. Various regions of interest inside skull; green area is the primary treatment volume. (top) Diagonal green lines from upper right to lower left are the boundaries of one beam. Note 3-D ruler measurement. (bottom) One "slab" of raw CT volume data is overlaid within the geometric contours of the patient's regions of interest, as enabled by functionality in the Spatial Visualization Environment.

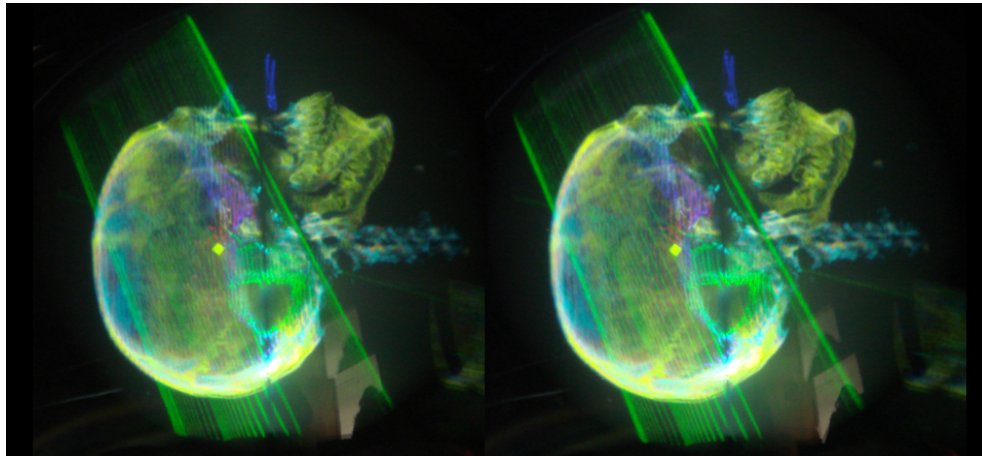


Figure 5: Cross-eye stereo photograph of PerspectaRAD image of superimposed geometrically-rendered anatomic regions of interest and beam trajectory and volume-rendered CT data.

A 3-D pointer is rendered in Perspecta, as controlled by a Phantom Omni 3-D haptic interface from SensAble Technologies (Woburn, MA, USA). Previous work had used magnetic or optical tracking for picking and pointing. However, it was judged that the Phantom Omni would be more affordable and less disruptive. Magnetic or optical tracking would require targets to be worn on the pointing fingers and a bulky installation, while the Phantom could fit on the table next to the volumetric display. A “3-D mouse” made by 3dconnexion (a descendant of the “SpaceBall”) was also considered, but it was felt that it would be more difficult to use. The Phantom moves the pointer a distance proportional to the distance moved by the pen, but a 3-D mouse moves the pointer proportional to the force applied. The force relationship is less natural than the distance relationship and requires some practice to become proficient.

The pointer is rendered in Perspecta with a decorated “X” shape that indicates both a location and a plane. The normal direction of the plane is determined by the Phantom’s stylus direction. The pointer can be “parked” by pressing a button on the stylus. When parked, the pointer color changes and the Phantom holds the pointer’s mechanical position stationary. The position can be incrementally nudged via XYZ spin boxes in the PerspectaRAD 2-D GUI. The user frees the stylus by toggling its button or gently snapping the stylus away from the parked position.

The PerspectaRAD application handles: Regions of Interest, Points of Interest, Beams, 3-D Images, and a Dose Volume. Each object class has a corresponding *class tab* in the 2-D main window. To control the amount of clutter in the volumetric rendering, each object class and each individual object can be independently enabled for display in Perspecta. Each *class tab* contains an *object browser*. The object browser lists all of the objects of the given class. The clinician can edit a particular object by clicking on it in the object browser. The state of the object appears in the *property editor*. Properties of the visual depiction of objects (such as their color) are imported from Pinnacle³, but they can also be controlled through the property editor. Points of Interest are rendered in Perspecta as small dots. They can be moved using the 3-D pointer. Regions of Interest are rendered using their contour lines. Several rendering modes are provided to clarify the relationship between the region of interest and the treatment plan. To visually emphasize the dose level within a Region of Interest, the contours can be colored by the dose level intersected by the surface. The intersection of the region with a beam (as defined by extruding the beam’s aperture along the beam’s axis) can be selected. The intersecting contours are then rendered with bold lines. This mode is useful for determining what portion of the organ is likely to be intersected by the given beam. The volume of intersection between the beam and the ROI can be calculated and the table of volumes overlaid on the 3-D image in Perspecta as alphanumeric text hovering in space.

In Perspecta, the central axis of each treatment beam is rendered. Also, the user typically displays the outline of the beam shape by clicking on a Render Beam Shape check-box. The selected beam orientation can be set to intersect the 3-D pointer position by pressing the front button of the Phantom. The beam direction can be “dragged” by holding down the button. The corresponding couch and gantry angles are computed and invalid angles are automatically rejected. The angles can also be entered numerically, using the 2-D main window. PerspectaRAD displays isodose shells, based on the radiation dose computed by the treatment planning workstation. Beam weights can be adjusted interactively with PerspectaRAD. The 3-D isodose shells are updated immediately when the beam weights are changed.

The main image is composed of one or more registered CT, MR and PET images. Each image is associated with a color map, which selects and colorizes a particular feature of the image. Color maps can be enabled and disabled separately, so that different combinations tissue types can be selected for view. The editor pane for the main image allows individual color maps to be added or deleted. Single-modality main images with up to 400 slices are supported, and each slice may contain 512x512 samples. Registered dual-modality images are supported, provided the images fit within the (approximately) 400 slice limit. Up to 220 MB of imagery may be loaded into PerspectaRAD. If the plan includes large datasets that overrun the available memory, an error message is issued and the plan will fail to load.

PerspectaRAD can display a complete volumetric image or it can display a set of arbitrarily oriented slices of the image data. This is illustrated in the bottom of Figure 4. If an image is enabled for display, the clinician can switch between these two modes by toggling the state of the checkbox in the “Mask” column of the “Images” tab. Slice masks allow one or more oblique slices of the 3-D image to be displayed in Perspecta (while the rest of the image is hidden). After a mask has been added, the clinician can use the Phantom’s stylus to capture the slice and move it around. The plane acts as a window into the image. Dragging the plane enables the clinician to view different slices of the image, and changing the “wrist” orientation of the Phantom controls the orientation of the slice in Perspecta. Any number of slice masks can be added, and each can be set to display a different colormap or volume image.

A radiation treatment plan may contain several “trials.” Each trial represents a separate attempt to optimize plan quality. PerspectaRAD can quickly switch among rendering different trials of a plan, so that they can be easily compared. The

system also has a mode to continuously cycle through the display of each trial. This can be used to arrange a simple animation, which can be useful for assessing the result as a particular parameter of the plan is continuously varied. For example, a set of trials were developed to illustrate gating effects on a lung tumor¹⁵.

The Ruler Profile tab can be used to display values that intersect with the ruler. When the ruler is active, the pointer endpoint of the ruler can be parked in same manner as the pointer. The endpoints of the currently drawn ruler can be changed via the spin boxes in the lower left hand section of the tab. On the 2-D main window a chart is drawn that depicts the dose or image density levels that intersect the ruler. A 3-D ruler measurement is shown at top of Figure 4. A large stereo photograph of the imagery is provided in Figure 5.

4. CLINICAL STUDIES

We summarize five retrospective clinical studies of PerspectaRAD that were performed in 2006 and 2007. The first three studies used the Perspecta Display v1.7 with a MATLAB-based “viewer” application. The final two used the Perspecta Display v1.9 with the interactive PerspectaRAD application discussed in the previous section. The new version allowed the display of gray scale and full-color images as well as the full roster of features described in Section 3.1, rather than only segmented contours. This provided a much improved visualization of structures as the user could highlight the preferred gray scale range of the image in the display.

The first study analyzed the potential of a volumetric display to assist in the understanding of candidate treatment plans¹³. During radiation therapy treatment planning, several plans are examined from which one is chosen for implementation. In the process of the evaluation, radiation dose regions are superimposed on the patient’s organ structures. These 3-D data sets are difficult to review efficiently in 2-D. Treatment plans were studied from eight patients with a variety of cancer sites. Four physicians reviewed the plans either on flat-panel displays or with Perspecta. The adequacy of target coverage was easily confirmed from different viewing angles when viewed in 3-D. The ability to see through the dose clouds and regions of interest due to Perspecta’s translucent imagery was valuable for assessing the plans. Physicians in the study confirmed that Perspecta reaffirmed their mental image of the volumes 97% of the time and provided additional insight 73% of the time. For 71% of the regions of interest with volumes ranging from 15 to 550 cm³, Perspecta enabled the physicians to achieve better estimations of dose coverage.

The purpose of the second study¹⁴ was to evaluate the spatial accuracy of the Perspecta 3-D Display prior to use as a planning tool. A reference frame was set up and the 3-D haptic mouse in PerspectaRAD was used to assess accuracy. Radiation doses at selected points were also compared to the reference. PerspectaRAD was found to consistently display accurate data at correct locations in 3-D, providing validation of the 3-D visual display, the 3-D mouse, and the software that interfaces with the treatment planning system. In all cases, the accuracy was less than the measurement error of 0.5 mm. It was concluded that the Perspecta Display is an accurate tool for both visualization and quantitative evaluations in radiation oncology.

The third study¹⁵ examined the potential role of volumetric displays in the analysis of moving, or so-called 4-D medical imaging data. A significant problem with treating lung cancer is that the tumor moves in all three Cartesian directions with each breath. The traditional solution is to treat the entire volume that the tumor moves around in, thus adding an unnecessarily large margin of healthy tissue. Advances in imaging are able to capture patient motion in time series of 3-D scans, registered with the breathing cycle in 10 steps. This third study looked at lung tumors and CT scans in 4-D for characterizing tumor shape and position during respiration. Perspecta and the visualization software successfully depicted the moving images of the lung in respiration, as well as tumor motion. Treatment plans were developed to demonstrate optimal positions in the breathing cycle for irradiating the lung tumor while minimizing the dose to healthy structures. There were considerable variations of dose distributions throughout the breathing cycle. For example, in a treatment plan trial, the fraction of lung receiving 20 Gy varied from 10% to 14% and the minimum tumor dose varied from 355 Gy to 654 Gy. Treatment margins could be reduced and dose escalation is possible if these variations were taken into account during planning. The study concluded that as treatment planning moves to 4-D, especially in the lung, volumetric displays will add significant value, as well as saving time in data review and planning.

The fourth study^{13,16} was initiated on a larger study group after the success of the first study; it was also the first in the series to use PerspectaRAD for the assessment rather than the MATLAB proof-of-concept. Using the first version of PerspectaRAD, a Perspecta display was interfaced to the Philips Pinnacle³ treatment planning system for reviewing 8 treatment plans on either traditional 2-D displays or in volumetric 3-D. Four physicians evaluated the value of the treatment plan using both display methods to judge insight, whether a plan needed improvement, and whether the

volumetric display confirmed their mental impression. Volume coverage for 74 regions of interest were evaluated in 2-D and 3-D. PerspectaRAD resulted in closer estimates 40% of the time and equal estimates 26% of the time. The use of a 3-D display did not always result in better volume estimates. The ability of visualizing 3-D images and translating them into accurate volume estimates may be highly user dependent. Nevertheless, visual estimates of volume coverage were accurate more often with the volumetric display than the 2-D display. The volumetric display improved subjective evaluation of the treatment plans. Finally, it was felt that PerspectaRAD provided visual information beyond what was available in 2-D displays, facilitating the treatment planning process.

The fifth study²⁶ increased the sample size to statistical significance. The study hypothesis was again that use of a volumetric display would lead to the production of better quality radiation therapy treatment plans. A randomized, prospective, multi-institutional study was conducted with 33 patients who had undergone treatment planning and treatment for cancer. Two treatment plans were produced for each patient, one based on a 2-D display alone and another produced in conjunction with PerspectaRAD. Two different planners were used for each patient to reduce bias. Plan quality was then evaluated by the same physicians who originally established the planning objectives, who were blinded to the planning device used. PerspectaRAD plans were better in 25 patients (60%), 2-D-only was better in 13 patients (31%), and both were equivalent in four cases ($p < 0.001$). (The analysis included nine patients from previous studies.) *Better plans* delivered lower doses to critical healthy organs. For example, PerspectaRAD plans identified as better achieved lower doses to the optic chiasm (up to 34% lower in dose), bladder (up to 17%), liver (up to 10%), kidney (up to 30%), and lung (up to 40%). The use of complex, non-coplanar beams was much more common with PerspectaRAD use. Although the mean target dose differed by less than 2% between rival plans, 57% of normal organs studied received less dose from PerspectaRAD plans. Many factors contributed to the development of a good plan, including, among others, planner skills, case complexity, physician directives, effectiveness of planning tools, and the amount of time available. The availability of a better display alone did not guarantee a better plan. The chances for producing a better plan when using PerspectaRAD ranged from 50% for brain to 82% for lung patients. No statistically significant association was found between plan preference and planning institution or planner. The study concludes that the use of the volumetric display in a majority of cases leads to better treatment plans in radiation therapy, indicating that continued development of this technology for clinical implementation is warranted. The planning process used for this study was described by Gong et al.²⁷

5. DISCUSSION AND FUTURE DIRECTIONS

We described the first interactive volumetric 3-D system for the iterative review and modification of radiation treatment plans. We examined the usefulness of providing an interactive volumetric 3-D projection of the patient anatomy and treatment plan by writing PerspectaRAD, a software application that links a standard planning workstation, Pinnacle³, to the Perspecta Spatial 3-D Display. The system enabled visualization and modification of complex 3-D plans. The outcomes of five studies strongly suggest that the technology merits further development as a commercially-available tool for the oncologist.

The series of clinical studies revealed suggestions and preferences that can guide the design of a commercial implementation of PerspectaRAD. For example, some users noted that the Phantom haptic interface causes fatigue when used for long periods. Although it adds to the learning curve of PerspectaRAD, a 3-D mouse like the ones made by 3dconnexion may be more appropriate for radiation treatment planning, where a dosimetrist would be working with the system continuously.

Plans made with PerspectaRAD were more often non-coplanar, meaning that the radiation beams are not all aligned within a single plane. Non-coplanar plans are more likely to have problems where the gantry would have to intersect with the patient or couch in order to form the specified beam angle. These collisions must be discovered during the planning process. While the gantry has sensors to prevent an actual collision with the patient or couch, such an error would require a re-plan, delay of treatment to the patient, and wastes valuable time in the treatment vault. Users requested a mode where the gantry and couch are depicted in the 3-D rendering, so that they can judge the likelihood of a collision, or so that the software could automatically detect it.

With the introduction of 4-D computerized tomography, new techniques are demanded to make the best use of the newly available temporal imaging, without over-burdening radiation treatment planners. As noted, it is possible to show a volumetric animation in Perspecta to get an intuitive feel for how the imaged anatomy is moving¹⁵.

However, it is difficult to work with a moving image where a specific plan and quantitative results are required. It is desirable to develop a static summary depiction of the dynamic imagery acquired with 4-D imaging. In “Color Intensity Projections” (CIP)²⁸, a transfer function is described that uses hue and saturation to visually describe the motion of tissue. The transfer function was used with 2-D slice renderings in order to assess whether respiratory gating was appropriate during external beam treatment. It would be interesting to develop a static volumetric rendering that summarizes tissue motion, as CIP does for slice rendering²⁸. Tensor visualization techniques would convey more information about the organ motion (in a static volume or slice rendering) than the scalar CIP transfer function^{29, 30}. The extra information would be useful if one were exploring the possibility of aligning a beam with the axis of motion.

A theme that emerged during the course of this work is that a treatment plan, whether for radiation therapy or surgical excision, should ideally correspond to the patient anatomy and the progress of treatment in a manner that is as up-to-date as possible. This is an area of active research. Systems that provide constantly-refined plans based on actual treatment delivery (e.g. the locations of brachytherapy seeds or the progress of a breast lumpectomy) may lead to procedures with more accuracy and therefore radically decreased side effects. Technologies that provide such *dynamic adaptive therapy* could be used with 3-D or 2-D displays to continue to improve the visualization and performance of numerous medical procedures. The application of 4-D imaging to radiation oncology, described above, is an early exploration of dynamic adaptive therapy.

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