Chapter 2
Plato's CAVE: A Multidimensional, Image-Guided Radiation Therapy Cross Reality Platform with Advanced Surgical Planning, Simulation, and Visualization Techniques Using (Native) DICOM Patient Image Studies

E. Brian Butler, Paul E. Sovelius, and Nancy Huynh

Abstract Plato's CAVE™ (Computer Augmented Virtual Environment) is a presurgical planning, multidimensional "situation clinical platform" designed, developed, and introduced to clinical practice by the Department of Radiation Oncology at Houston Methodist Hospital, located in Houston's Texas Medical Center. At approximately 500 square feet, Plato's CAVE was specifically designed to permit a team of physicians to review all available diagnostic images of the patient. The initial clinical focus was on interventions within the domain of surgical oncology/radiation oncology including radiation therapy, reconstructive surgery, and organ transplantation. This advanced clinical visualization process, supported by a novel and creative assemblage of FDA-approved, commercially available diagnostic imaging components, is available for all relevant patient care services within The Methodist Hospital System.

Keywords Cave • DICOM • Radiation oncology • Dual reality • Surgical planning • Visualization • Image-guided therapy • Liver cancer • Interactive graphics • Stereoscopy • Virtual reality • High definition

The fundamental principles in image-guided radiation oncology treatment simulation can be applied to surgical oncology. These principles include the following (1) imaging the patient in the exact position that they will be treated in, (2) creating a three-dimensional image of the patient that the radiation oncologist can interact with his/her scalpel (the radiation beam), (3) looking for the best entry point to attack the tumor or target, and (4) evaluating the volume of normal tissue that is going to be destroyed by the tool (radiation beam). The Plato's

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M. Garbey et al. (eds.), *Computational Surgery and Dual Training: Computing, Robotics and Imaging*, DOI 10.1007/978-1-4614-8648-0_2,

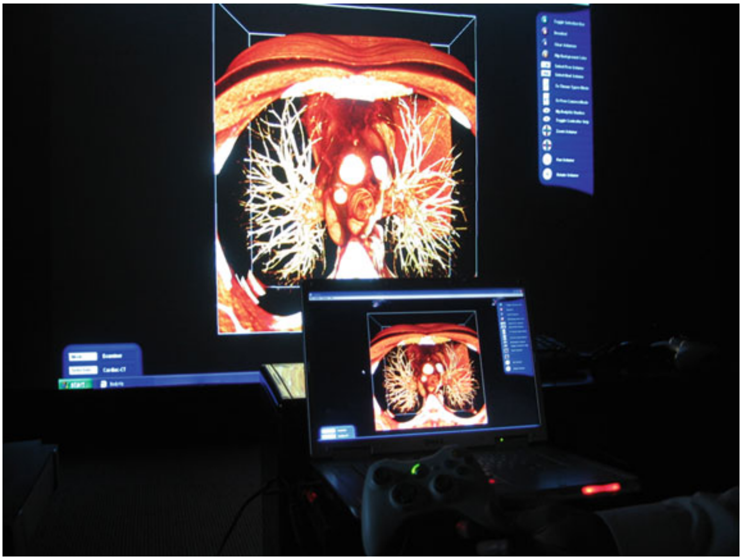

Fig. 2.1 Large screen (stereoscopic capable) with laptop and X-Box controller

CAVE [1] strategic vision and tactical concepts are well on their way to combining the fundamental principles in radiation oncology to augmented surgical planning with improved crystal clear visualization. This visualization process integrates the original Massachusetts Institute of Technology (MIT) concept of dual reality [2] (virtual world integrated with real world) with a new more appropriate phrase, cross reality systems (CRS) [3] from MIT. CRS bring together the sensor and actuator networks of ubiquitous computing or the interface between worlds and will provide Plato's CAVE's "intuitive advanced surgical visualization" technology with a much richer clinical and research 3D volume visualization experience (Fig. 2.1). For the surgeons this CRS process of intervention complemented with the current standard of care imaging will save evaluation time, the most valuable resource a physician or surgeon has available to them. This is possible in part thanks to computer processing power, enhanced graphics cards, three-dimensional LED monitors, and the ability to store large amounts of data, locally or in a cloud and transfer the data to a location where there is processing and interactive feedback loop capability. These additional capabilities allow the surgeon to create a virtual patient that they can interact with by using custom volumetric interactive tools resulting in a presurgical and radiation oncology flight simulator for multi-session treatment plans. The ability to interact with multidimensional, volumetric, and stereoscopic data is dependent on how the Digital Imaging and Communications in Medicine (DICOM) imaging acquisition protocols are ordered and the use of the optimal contrast agent to enhance the surgeons regions of interest.

Our research over the past decade has been focused on image-guided radiation therapy (IMRT) and image-guided gene therapy (IGGT). In the past year, we have broadened our focus to include "visualization-guided" clinical interventions that are within the domain of surgical oncology/radiation oncology, including reconstructive surgery and transplantation, supported by a novel and creative assemblage of FDA-approved, commercially available components. This expansion of our focus has been made possible by our team's development of an *N*-dimensional (space, time, discrete color, and multi-modality images) image-guided visualization system that has been operational in our laboratory since April 2009. The underlying concept is that of a flight simulator in that it enables pre-intervention 3D visualization, planning, and training. The difference is that it also enables almost real-time (within seconds) intra- and post-operative visualization of the process and the outcomes immediately and over whatever time period may be desired for follow-up. This visualization technology is indifferent to the image acquisition modality and to whether the images are at the scale of molecules and cells or a whole organ, anatomical region, or whole body. It needs to conform to evolving DICOM standards [4].

Our group's fundamental purpose is to process, from a patient's existing DICOM image studies that are either retrieved from the acquisition modality console, hospital PACS system or loaded on site from outside sources via electronic transfer, CDs, or DVDs. This 3D volume visualization of the patient is measurable, volumetric, and stereoscopic. This approach allows us to take advantage of the strengths of each imaging modality by fusing all of the images available for the patient (CT, MRI, PET, and ultrasound) in a sequence of events that are relevant to the multidisciplinary treatment team.

We have begun to develop, adapt, and test CRS tools, i.e., physical devices synched with a virtual clone of the device enabling a simple, seamless operator interaction with the volumetric visualization of the patient. The virtual tools are being designed to mimic the way surgeons use the real device. In addition, these CRS tools will allow for measurement and quantification of processes within the virtual patient (e.g., size of obstruction within a blood vessel, liver volume, location of an obstruction within the bile duct, and how a pancreatic carcinoma encases the superior mesenteric artery and vein). This allows the physician to interact with the virtual patient before he/she performs a procedure. We can also record a path or scenario that can act as a look-ahead avoidance system, something the current robotic devices do not permit. This interaction will occur in numerous ways, for example, a promising method of interaction involves utilization of a flat-panel, multi-user, multi-touch "virtual surgical table (VST)" (Fig. 2.2). The VST allows multiple users (4 to date) to interact simultaneously with the virtual patient in part or in whole in a 1:1 mapped relationship coordinated with a large screen. Techniques and processes are being refined for capturing, via high-definition video, a surgeon's eye-hand movements while performing an intervention in the operating room that will enable us to build feedback loops based on haptic, hand gesture, voice, and eye tracking interaction between the operator and the patient volume visualization synchronously as it appears on the surgical table.

We are now focusing our efforts on a systematic evaluation of organ systems and related disease processes. The hepatobiliary system provides a good example

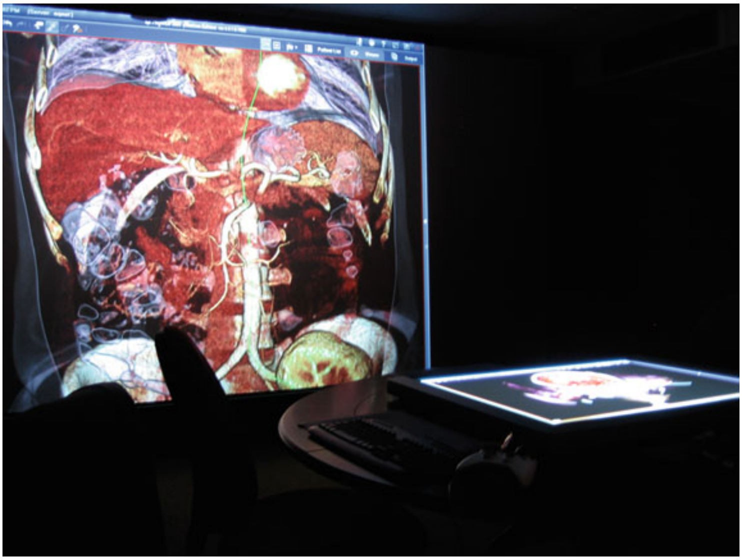

Fig. 2.2 Virtual surgical table

of the importance of doing this with high fidelity visual data (Fig. 2.3). Measuring the volume [5, 6] of this difficult to image organ is key to clinical decisions with respect to cancer diagnosis and therapy, among other medical conditions. However, even simple volumetric evaluation represents a paradigm shift in the way cancers are staged. Conventional staging of liver cancer is based on a single dimension. Typically, "size" as measured on axial CT or MRI images is a major consideration so that, for example, a 5 cm lesion will be classified as stage T2. In contrast, volumetric evaluation brings in the other two dimensions and may change the staging in significant ways. We now evaluate all tumors volumetrically and have begun mapping the arterial and venous branches so that surgeons can clearly avoid them while performing a resection.

Prior to performing a virtual surgical procedure the following evaluation of the patient's specific standard 2D and 3D volumetric data set would take place: (1) fusion of all available DICOM data; (2) 3D evaluation of the arterial and venous blood supply (including a "fly through" of the blood vessels, down to sub-millimeter); (3) evaluation of the ductal system; (4) evaluation of the liver pre- and post-virtual resection; (5) evaluation of the phenotypic visual pattern of the liver and the tumor in relation to genetic profiling of the tumor; and (6) evaluation of the volume of the tumor resected in the real patient compared to the virtual pre-surgery calculation. Since April 2009, we have clearly demonstrated that patient-specific standard of care images that are acquired for primary diagnostic imaging are inadequate for very thin slice 3D volumetric surgical intervention and our institution has adjusted and changed the image acquisition protocols based on the oncology-surgical procedures being refined (Fig. 2.4).

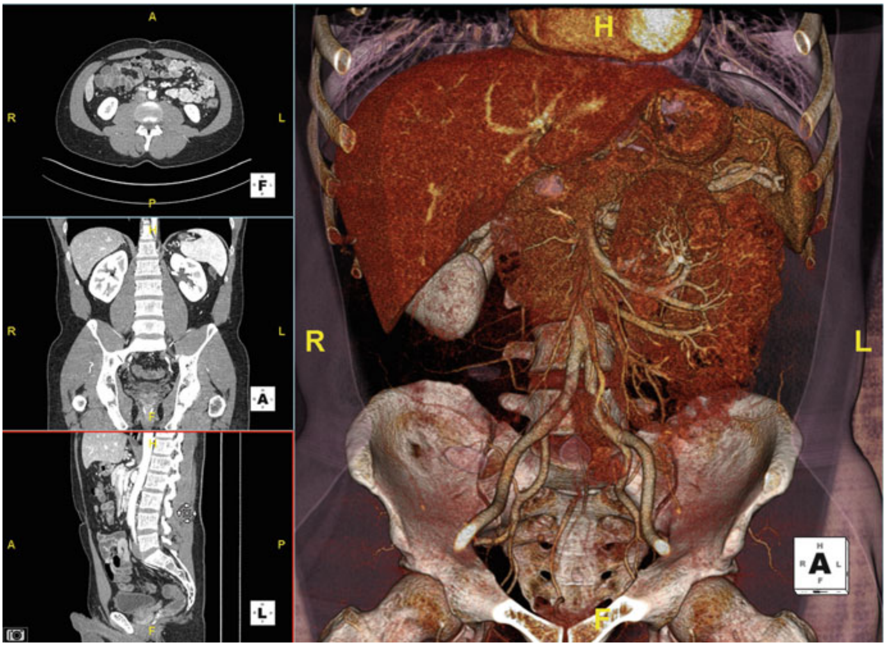

Fig. 2.3 Liver surgical resection review—standard image review of care vs 3D volumetric analysis

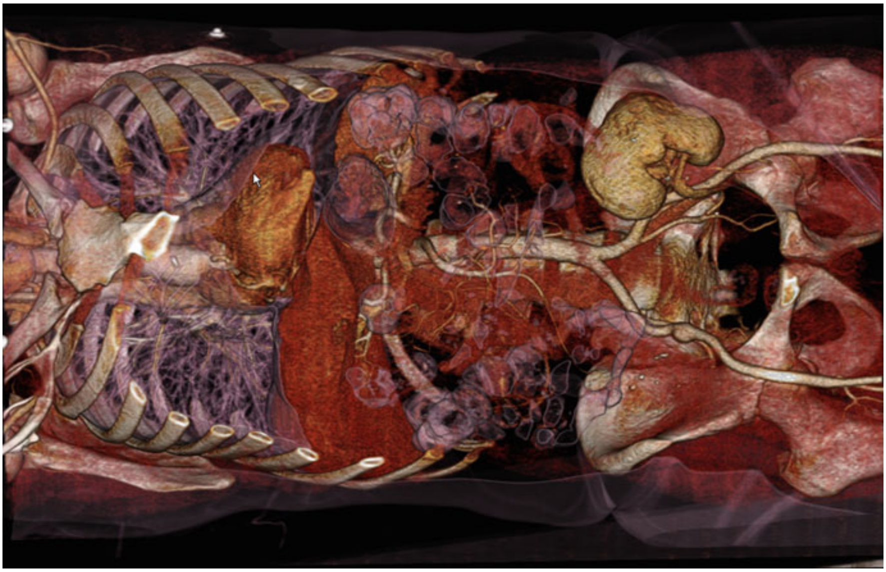

Fig. 2.4 CTA liver 3D volumetric reconstruction data courtesy OSIRIX

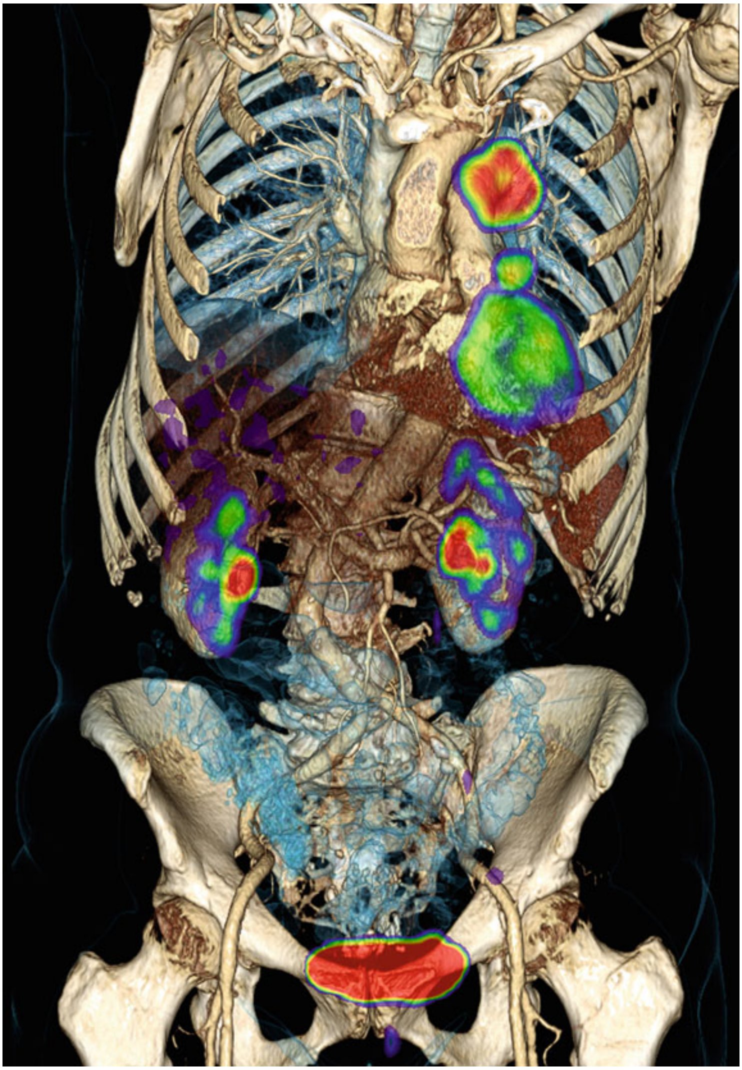

Fig. 2.5 Ancillary findings with CT and PET fusion

This evolving platform offers enormous opportunity for education of the primary care physician, referring physician, patient (and family), medical students, residents, surgeons, and radiation oncologists by narrowing the degree of uncertainty that each brings to the interaction. In the same way, it gives the team of surgeon, medical oncologist, and radiation oncologist the ability to make the most informed decision regarding the best treatment of the disease as it has been diagnosed. In some cases, the visualization has revealed previously unrecognized, complicating ancillary anatomical findings or additional disease complications (Fig. 2.5).

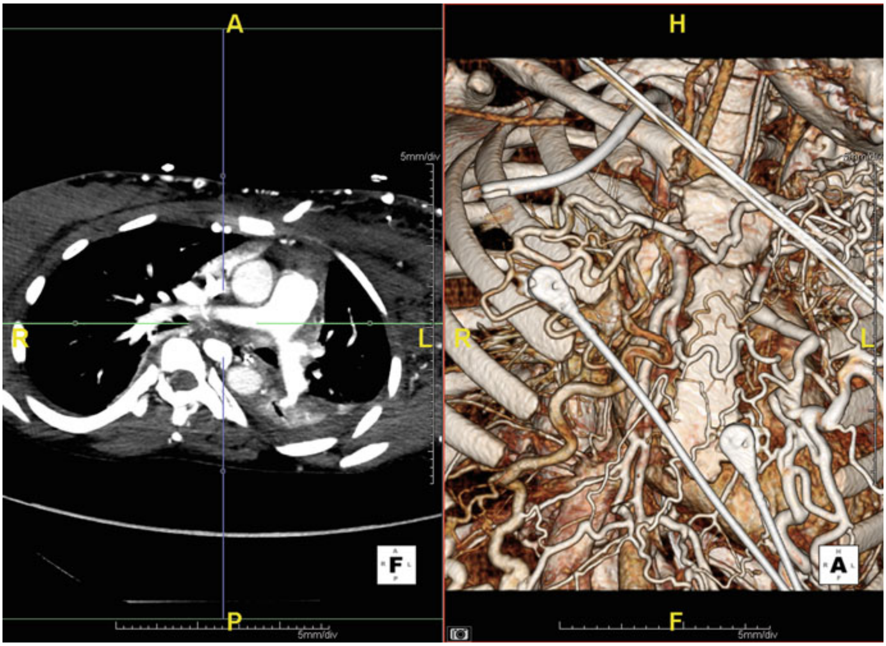

Fig. 2.6 Pre-surgical review for esophageal varices planning ancillary findings

The development, testing, validation, and translation of this technology into clinical practice are progressing in a systematic manner. We anticipate that more refined tools (instruments) will be developed to interact with the virtual patient. Ultimately the images that are fused to create the virtual patient will be registered and superimposed to the real patient and the instruments will interact with the patient providing clinical interventions of the highest quality and safety for the patient. At the fundamental level, this system has universal applicability across all medical specialties and subspecialties (not just surgery) and will allow the patient and the physician to understand disease processes in ways never before possible.

This system has generated a great amount of interest in new capabilities among surgical colleagues at Houston Methodist Hospital, Texas Children's Hospital and elsewhere. Some of them have used it to perform their pre-surgery assessment, evaluation and planning even to the extent of revising initial treatment plans that were based on conventional 2D, black and white images (Fig. 2.6). Some have used Plato's CAVE visualization to explain to their patients the nature of their clinical situation and the choice of a particular surgical approach. The surgeons are confident with the quality of the visualization, the ease and speed with which positions of the images can be changed, the ability to strip away tissue that blocks the view of the subject tissue, and the fact that in some situations, no contrast agents are required to achieve a sophisticated level of the visualization (Fig. 2.7).

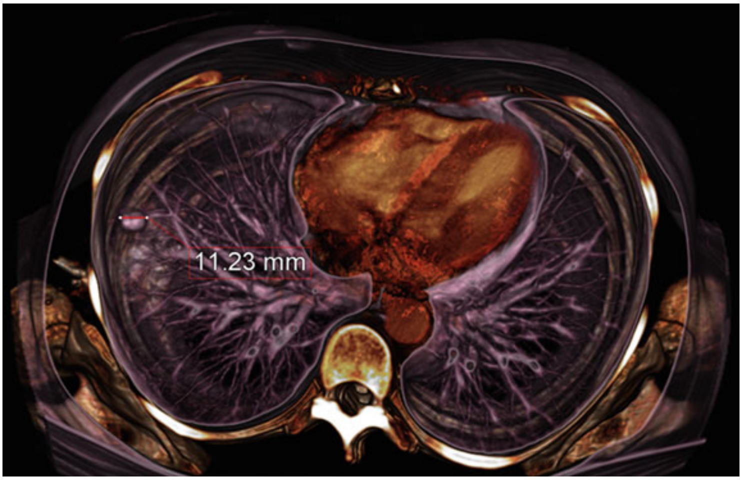

Fig. 2.7 CT volumteric of lung with standard staging

The application to image guided disciplines at the macroscopic level will move to image guided nanoshell delivery (IGND) [7] with payloads that include gene therapy [8], chemotherapeutic, and immunological payloads. We recognize that applications to surgery/radiation therapy only scratch the surface of the system's potential to advance research, clinical medicine, and medical education as is suggested by our working name: "Plato's CAVE." We think this name is appropriate since it describes the human condition when knowledge is restricted by physical and technological limits and bounded vision. Emergence from the CAVE leads to new and boundless vision and opportunity—thus, the revolutionary character of our system is just beginning to be revealed and realized, while at the same time visions for an expansive future grow almost daily.

This visualization technology is equally usable with molecular, cellular images and gene expression cluster analysis [9] mapped to the clinical image, regardless of the image acquisition modality; adaptable to all surgical interventions from reconstruction through transplantation; and capable of bringing quantum improvements to the diagnosis and treatment planning for nearly all diseases and medical conditions. It may be important to note that this visualization technology is totally complementary to all current and developing conventional imaging modalities. We are using phase one of this multi-use technology on a daily basis and, as our surgeons have discovered, once they work with this system they cannot justify returning to the current standard images and presentation of these images for their patients. The CAVE's fundamental technology was designed to be part of a collaborative physician GRID (https://cabig.nci.nih.gov/). Plato's CAVE interactive, collaborative visualization can be distributed to the scientist's or clinician's desktop or conference room, just as easily as it is to the OR, since it is server based, thin client enabled, HIPAA compliant and extremely interactive.

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Computational Surgery and Dual Training
Computing, Robotics and Imaging
Garbey, M.; Bass, B.L.; Berceli, S.; Collet, C.; Cerveri, P. (Eds.)
2014, XII, 394 p. 156 illus., 114 illus. in color., Hardcover
ISBN: 978-1-4614-8647-3