

CT Simulation Refresher Course

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I. INTRODUCTION

The radiation therapy simulator has been an integral component of the treatment planning process for over 30 years. Conventional simulators are a combination of diagnostic x-ray machine and certain components of a radiation therapy linear accelerator. Consisting of a diagnostic quality x-ray unit and fluoroscopic imaging system, the treatment table and the gantry are designed to mimic functions of a linear accelerator. The images are transmission radiographs with field collimator settings outlined by delineator wires. Using primarily bony landmarks a physician outlines areas to receive therapeutic radiation doses. One shortcoming of a conventional simulation process is that very little anatomy, other than bony anatomy, is available for design of treatment portals.

CT images provide information not only about target volumes but about critical (normal) organs as well. Using CT images for radiation therapy treatment planning has enabled us to improve dose delivery to target volumes while reducing the dose to critical organs. CT images also provide density information for heterogeneity-based dose calculations. A major weakness of CT images is a relatively limited soft tissue contrast. This, limitation can be overcome by using CT images in conjunction with magnetic resonance (MR) studies for treatment planning. Positron emission computed (PET) images can be used to add physiological information.

In 1983 Goitein and Abrams^{1, 2} described multidimensional treatment planning based on CT images. They described a “beam’s-eye-view” (BEV) function which “provides the user with an

accurate reproduction of anatomic features from the viewpoint of a treatment source”. They also described how “projection through the CT data from any desired origin provides an alignment film simulation which can be used to confirm accuracy of treatment, as well as help establish anatomic relationships relative to the margins of a treatment field”. This was a description of major characteristics of a system known today as the CT-simulator. An alignment film created from a divergent projection through the CT study data is commonly known today as the digitally reconstructed radiograph (DRR). Sherouse et al³ further discussed DRR use in radiation therapy.

Sherouse et al^{4, 5} also described a CT image based virtual simulation process which they referred to as a “software analog to conventional simulation”. This series of publications described software tools and addressed technical issues that affect today’s CT-simulation process. They also described the need for fast computers, specialized software, but also for improved patient immobilization and setup reproducibility.

Several other authors also described the CT simulation process⁶⁻⁸. These authors outlined several problems associated with CT simulation: 70 cm CT scanner bore inadequate for large patients and asymmetric setups, transfer of volumetric CT data slow, difficulty with image analysis (requires diagnostic expertise), time consuming contouring, slow generation of DRRs, quality of printed graphic display (hardcopy), inconsistent accuracy, necessity of physical simulator verification.⁸ Some of these have been overcome (scanner bore size, speed of data transfer, speed of DRR generation, hardcopy quality) while others are still not completely resolved.

One of the early commercial CT simulation packages (introduced in 1994) which is probably the most often described system in literature is shown in Figure 1. (AcqSim Oncodiagnostic Simulation/Localization System, Marconi Medical Systems, Inc. (formerly Picker International) Cleveland, OH).

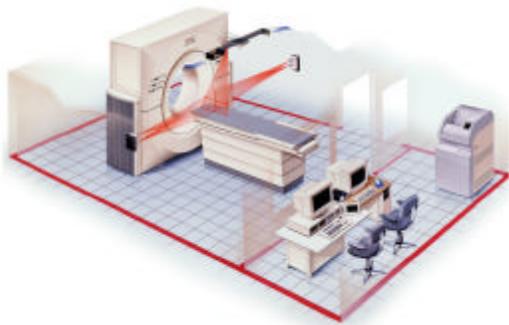


Figure 2. CT-Simulator. (Courtesy Marconi Medical Systems, Inc.)

II. CT SIMULATOR COMPONENTS

CT simulator consists of a diagnostic quality CT scanner, laser patient positioning / marking system, virtual simulation / 3D treatment planning software, and different hardcopy output devices. The CT scanner is used to acquire a volumetric CT scan of a patient which represents the virtual patient and the simulation software creates virtual functions of a conventional simulator. Proper selection of components of a CT-simulator or a CT-simulator as a commercial package is very important, as they will notably affect the rest of the treatment planning and delivery process in a clinic.

a) CT scanner

Generation - Common historical CT scanner classification is into four generations⁹:

First generation - x-ray tube and a single detector translate and rotate together,

Second generation - involved multiple detectors, x-ray tube translated and rotated,

Third generation - fan beam geometry with multiple detectors, x-ray tube and detector rotate together,

Fourth generation - fan beam geometry with a complete rotation of the x-ray tube around a stationary ring of x-ray detectors.

Scanners commercially available today are either 3rd or 4th generation. Both scanner generations give excellent images with no significant advantages of one over the other.

X-ray tube - Two characteristics of CT simulation process guide requirements for the X-ray tube selection:

a) *Large number of images per study*- CT studies for image based radiation therapy treatment planning and CT-simulation involve larger number of images per patient than in diagnostic radiology. Depending on the treatment site and the length of the scanned volume, typically 80 to over 200 images per patient are acquired.

b) *Rapid study acquisition time*- A CT simulation study should be imaged in a single rapid acquisition. Rapid scan time minimizes motion artifacts (due to breathing or patient movement). In addition, if the scanned volume is not imaged in a single continuous acquisition; the patient can move between acquisitions and distort the spatial integrity of the study.

CT simulator X-ray tube must have large heat anode loading and heat dissipation capabilities to withstand the very high heat loads associated with the large number of images acquired in a rapid sequence.

Scan geometry- Axial or Spiral (Helical) - Axial and spiral scanning modes have been described in many publications⁹⁻¹².

Virtually all modern scanners are spiral (helical) machines. These scanners are capable of continuous x-ray tube rotation while the couch is moving during the scan procedure. In spiral scanning, as the x-ray tube rotates around the patient, the couch moves the patient through the imaging plane and the scanner gantry. The resultant path geometry that the x-ray tube describes around the patient is a spiral or helical winding. With this technique, volumes of tissue rather than single

slices are acquired, so the technique is sometimes referred to as volumetric scanning¹³. Spiral imaging is capable of sub-second image acquisition times. Fast imaging makes spiral scanning the preferred choice for CT simulation.

Single-slice and multi-slice scanning- In 1992, Elscint CT Twin was introduced as the first CT scanner capable of simultaneously acquiring more than one transaxial slice. In 1998, four more manufacturers introduced their versions of multi-slice scanners. These scanners were capable of acquiring four simultaneous slices. Manufacturers are in various stages of developing scanners capable of acquiring at least 8 simultaneous slices.

The main advantage of multi-slice scanners is the ability to acquire images faster than single slice scanners¹⁴⁻¹⁶. A four-slice system with a 0.5 second rotation can acquire volume data up to 8 times faster than a single slice machine with a 1 second rotation. Due to the longer length of imaged volume per tube rotation (multiple slices simultaneously), the tube heat loading during a scan of a certain patient volume is lower for multi-slice than for a single-slice scanner. This allows thinner slice thickness to be used for scanning or longer volumes to be scanned. Faster acquisition times, decreased tube loading (which will allow longer volumes to be scanned in a single acquisition), and thinner slice thickness associated with multi-slice scanners can potentially provide advantage over single-slice systems for CT simulation purposes.

Bore (gantry opening) size- When patients are scanned for diagnostic purposes they are typically in a supine position with their head towards the gantry, arms at their side or on their chest, and their legs extended. Diagnostic CT scanners have predominantly 70 cm bore openings. This is quite adequate for diagnostic scan purposes. For CT simulation purposes, patients are often in positions that can prevent them from entering the 70 cm bore opening. For example, breast treatments where the ipsilateral arm is subtended at close to a 90° angle frequently have difficulty entering the 70 cm bore. Inability to simulate all patients in an optimal

treatment position due to restricted bore opening has often been cited as one of the major weaknesses of the CT simulation process^{8, 12, 17, 18}. Marconi Medical Systems, Inc. has manufactured a scanner specifically designed for radiation oncology purposes with an 85 cm bore opening. The first unit was installed in December 2000 at Mallinckrodt Institute of Radiology in St. Louis.

The enlarged opening allows entry of immobilization devices and patients in positions that are commonly used in radiation oncology, Figure 2. Image performance of the large bore scanner is comparable to 70 cm bore diagnostic scanners¹⁹. The 85 cm bore scanner also has increased scanned field of view (SFOV)--60 cm compared to 48 cm on most 70 cm bore units. Increased SFOV allows for full visualization of larger patients and immobilization devices. This feature is important to fully assess patient external dimensions which are necessary for accurate dose and monitor unit calculation. Due to the superior patient setup and immobilization flexibility and larger SFOV, the 85 cm large bore scanner is proving to be a valuable tool in CT simulation.

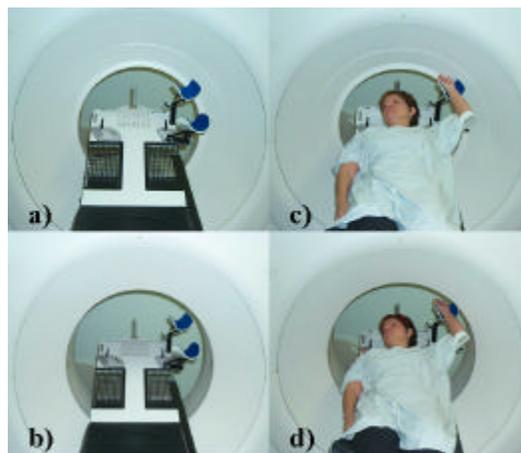


Figure 2. Comparison of 70 cm and 85 cm bore opening; a and b) breast board in front of 70 cm and 85 cm bore, respectively, c and d) breast CT simulation with a breast board in front of 70 cm and 85 cm bore, respectively.

Couch- CT simulator couch should have a flat top similar to radiation therapy treatment machines. Additionally, it should accommodate commercially available registration devices. The registration device allows patient immobilization device to be moved from the CT simulator to a treatment machine, in a reproducible manner. The couch should have sag of less than 2 mm. This is in accordance with specifications for linear accelerators²⁰. The couch weight limit should be comparable to those of medical linear accelerators (at least 400 to 450 lbs).

Patient marking lasers- A laser system is necessary to provide reference marks on patient skin or on the immobilization device. Figure 1 shows the laser system for a CT simulator:

Wall lasers – Vertical and horizontal, mounted to the side of the gantry and typically immobile

Sagittal laser – Ceiling or wall mounted single laser, preferably movable. Scanner couch can move up/down and in/out but can not move left/right, therefore the sagittal laser should move left/right to allow marking away from patient mid line.

Scanner lasers – Internally mounted, vertical and horizontal lasers on the either side of the gantry and an overhead sagittal laser.

Lasers should be spatially stable over time and allow for positional adjustment.

Image quality performance- The corner stone of 3D conformal radiation therapy (3DCRT) treatment planning are patient images. These should be high quality diagnostic type images and the CT simulator should be capable of producing these types of images. When purchasing a CT simulator, image quality should be one of the top concerns. At the very least, the following image quality indicators⁹ should be considered:

Spatial resolution – measure of the scanner's ability to discriminate objects of varying density a small distance apart against a uniform background. Specified in line pairs per cm (Lp/cm).

Low contrast resolution – the ability of an imaging system to demonstrate small changes in tissue contrast. Specified as the ability of the CT unit to image objects 2 to 5 mm in size which vary slightly in density from a uniform background.

Noise – the fluctuation of CT numbers from point to point in the image of a uniform object.

Cross-field uniformity – the uniformity of CT numbers throughout the entire scan field. This performance characteristic can potentially be important in heterogeneity-based dose calculations.

Hard copy printers – DRRs can be printed on paper or on film using laser film printers. DRRs printed on film are generally much easier to use and often preferred.

b) Virtual simulation/3D treatment planning software and workstation

As with all software programs, user-friendly, fast, and well functioning virtual simulation software with useful features and tools will be a determining factor for the success of a CT simulation program. Several features are very important when considering virtual simulation/3D treatment planning software:

Contouring and localization of structures – At present, contouring and localization of structures is often mentioned as one of the most time consuming tasks in the treatment planning process. The software should allow for fast, user-friendly contouring process with the help of semi-automatic or automatic contouring tools.

Image processing and display - Virtual simulation workstation must be capable of processing large volumetric sets of images and displaying them in different views as quickly as possible (near real time image manipulation and display is desired). The following are some of the important display capabilities:

Digitally reconstructed radiographs (DRRs) - DRR is a divergently corrected reconstructed radiograph, Figure 3, produced by projecting ray-lines through volumetric CT data set². The image is equivalent to a conventional transmission radiograph but is created using a virtual x-ray source and imaging plane.

Digitally composited radiographs (DCR) - DCR is created similarly to DRR. The difference is that various ranges of CT numbers that relate to certain tissue types are selectively suppressed or enhanced in image creation, Figure 3b. The created image is analogous to a transmission radiograph through a virtual patient whose certain tissue types have been removed leaving only organs of interest to be displayed.

Multipolar reconstruction (MPR) - CT study consists of axial images in its native form. Multipolar reconstruction allows for creation of images in arbitrary planes (coronal, sagittal, oblique, vertex) from volumetric axial data set, Figure 4 (right lower image).

Various other displays - The software should be capable of producing room views, 3D reconstructions of a patient, etc. The virtual simulation system should be able to display all of these views simultaneously, Figure 4.

Simulator geometry - A prerequisite of virtual simulation software is the ability to mimic functions of a conventional simulator and of a medical linear accelerator. The software has to be able to account for gantry, couch, collimator and jaw motion, SSD changes, beam divergence, etc. The software should facilitate design of treatment portals with blocks and multileaf collimators.

Fusion/Multimodality imaging registration - Imaging modalities other than CT are useful in accurately delineating tumor volumes²¹⁻²³. Magnetic resonance imaging (MRI), magnetic resonance spectroscopy (MRS), single photon emission computed tomography (SPECT), and positron emission tomography (PET) are imaging modalities which can provide unique target information and may improve overall radiation

therapy patient management²⁴⁻²⁶. All of these imaging modalities provide valuable treatment planning information that complement each other.

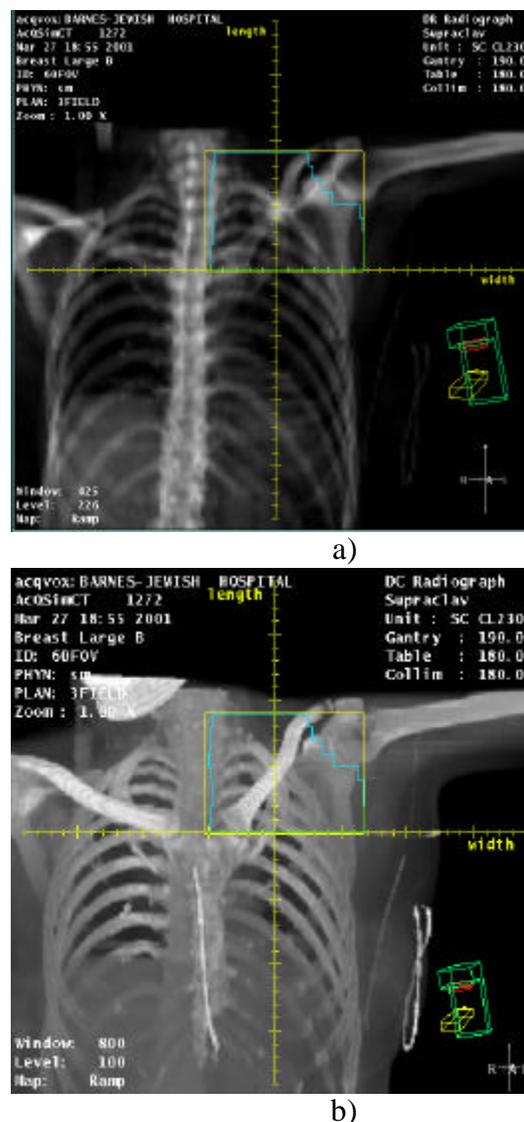


Figure 3. a) Chest DRR, b) Chest DCR.

When multiple imaging studies are employed, they must be spatially registered to accurately aid in tumor volume delineation. Registration of multimodality images is a several-step process requiring multi-function software capable of image set transfer, storage, coordinate transformation, and voxel interpolation.

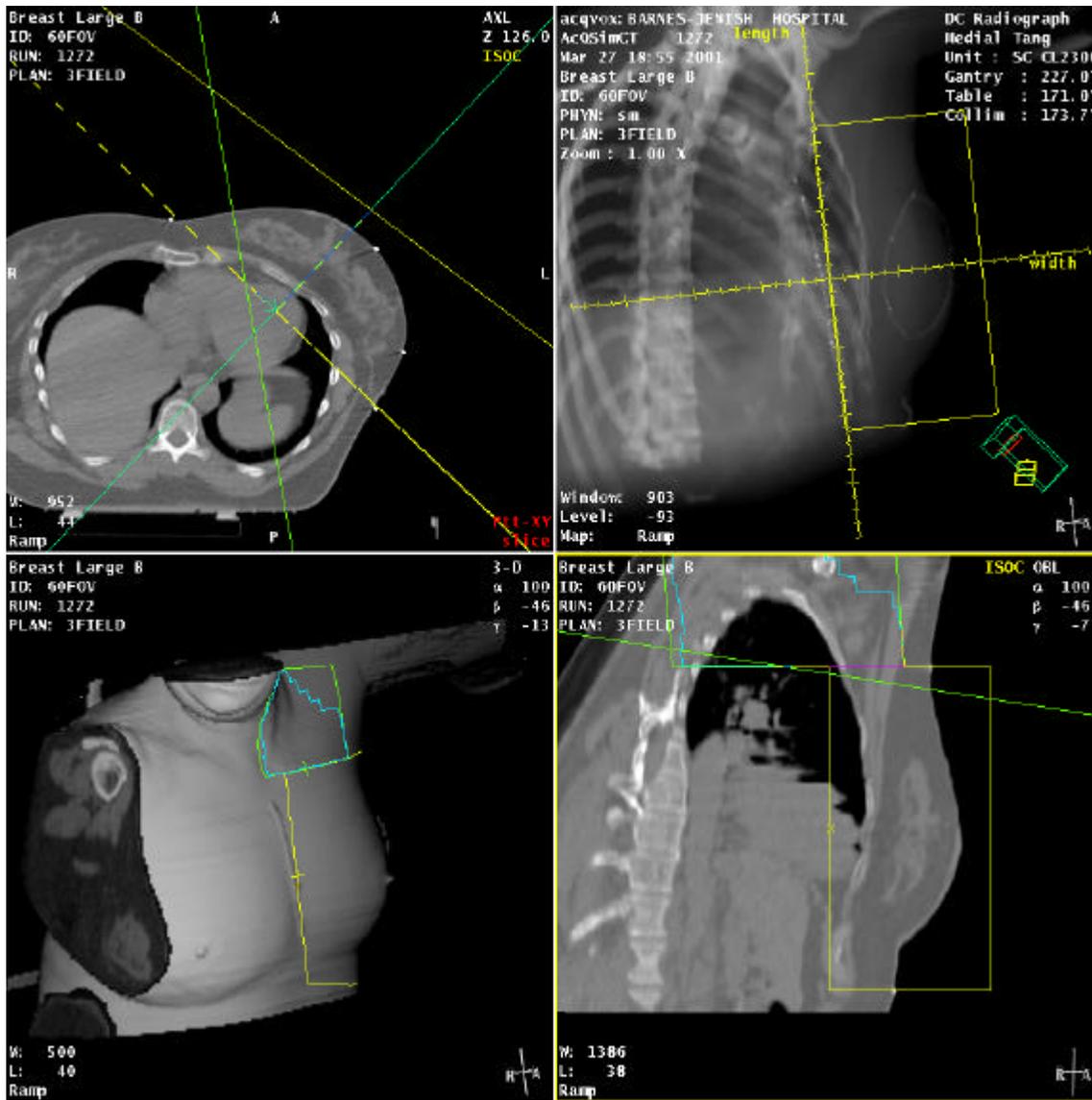


Figure 4. Simultaneous display of an axial image, 3D display, DCR, and a MPR image.

Connectivity - Virtual simulation workstation is commonly the first step for image transfer between the CT scanner and various treatment planning computers, record and verify systems, and treatment delivery machines. When purchasing new software, the manufacturer should provide the “DICOM conformance” statement; from the Radiological Society of North America, Inc. web-site (<http://rsna.org/practice/dicom>). “DICOM (Digital Imaging and Communications in Medicine) is the industry standard for transferal of radiologic images and other medical information between computers. Patterned after the Open System Interconnection of the International Standards Organization, DICOM

enables digital communication between diagnostic and therapeutic equipment and systems from various manufacturers.”

“DICOM conformance” means the manufacturer states that the software can communicate with other DICOM conformant products. The conformance statement will list all DICOM functions that are implemented. A comparison of conformance statements from each product should reveal potential communication problems. In addition, one should contact other health care institutions with similar equipment to verify that connectivity between products actually works.

Dose calculation - Virtual simulation workstation can also have 3D dose calculation and display capabilities. The dose calculation software should have capabilities that are commonly found on other 3D treatment planning systems²⁷⁻³⁰.

III. CT SIMULATION PROCESS

CT simulation process has been described by several authors^{4, 12, 17, 18, 31, 32}. The process includes the following steps:

- Patient positioning and immobilization
- Patient marking
- CT scanning
- Transfer to virtual simulation workstation
- Localization of initial coordinate system
- Localization of targets and placement of isocenter
- Marking of patient and immobilization devices based on isocenter coordinates
- Contouring of critical structures and target volumes
- Beam placement design, design of treatment portals
- Transfer of data to treatment planning system for dose calculation
- Prepare documentation for treatment
- Perform necessary verifications and treatment plan checks

This process and its implementation vary from institution to institution. The system design is dependent on available resources (equipment and personnel), patient workload, physical layout and location of different components and proximity of team members.

a) CT Scan, Patient Positioning and Immobilization

The CT simulation scan is similar to conventional diagnostic scans. However there are several particularities. Patient positioning and immobilization are very important. Scan parameters and long scan volumes with large number of slices often push scanners to their technical performance limits.

Patient positioning and immobilization - The success of conformal radiation therapy process

begins with proper setup and immobilization. Positioning should be as comfortable as possible. Patients who are uncomfortable typically have poor treatment setup reproducibility. Immobilization devices tremendously improve reproducibility and rigidity of the setup. Patient setup design should consider location of critical structures and target volumes, patient overall health and flexibility, possible implants and anatomic anomalies, and available immobilization devices.

Scan protocol - The CT scan parameters should be designed to optimize both axial and DRR image quality and rapidly acquire images to minimize patient motion^{9, 18, 32-35}. The parameters influencing axial and DRR image quality include: kVp, mAs, slice thickness, slice spacing, spiral pitch^{10, 11}, algorithms, scanned volume, total scan time, and field of view (FOV).

Scan Limits - Scan limits should be specified by the physician and should encompass area at least 5 cm away from the anticipated treatment volumes. Slice thickness and spacing do not have to be constant throughout the entire scanned volume. Areas of interest can be scanned with narrow (3 mm) thickness and spacing, while large slices (5 mm) can be used for scanning surrounding volumes. This will maintain good DRR quality while minimizing tube heat.

Contrast - For several treatment sites contrast can be used to help differentiate between tumors and surrounding healthy tissue.

Reference Marks - During the CT scan a set of reference marks must be placed on the patient so the patient can be positioned on the treatment machine. When and in relationship to which anatomical landmarks the reference marks are placed can be performed in two different ways.

No shift method - for this method patient is scanned and, while the patient is still on the CT scanner couch, images are transferred to the virtual simulation workstation. The physician contours the target volume and the software calculates the coordinates of the contoured volume center. The calculated coordinates are transferred to the CT scanner, the couch and the movable sagittal laser

are placed at that position and the patient is marked using pen or tattoos).

Shift method - this method does not require physician to be available for the CT scan. Prior to the scan procedure, based on the diagnostic workup (CT, MRI, PET, palpation, etc.), the physician instructs CT simulator therapist where to place the reference marks on the patient. After the scan is done and the patient goes home, the physician contours target volumes and determines the treatment isocenter coordinates. Shifts (distances in three directions) between the reference marks drawn on the CT scanner and the treatment isocenter are then calculated. On the first day of treatment, the patient is first positioned to the initial reference marks and then *shifted* to the treatment isocenter using the calculated shifts.

b) Virtual simulation

Virtual simulation process typically consists of contouring target and normal structures, computation of the isocenter, manipulation of treatment machine motions for placement of the beams, design of treatment portals, printing of DRRs and documentation. This process is largely dependent on the software capabilities. Also there are well designed methods for simulating specific treatment sites. Several publications describe these methods in detail^{12, 17, 31, 32, 36-38}.

IV. QUALITY ASSURANCE

Quality assurance (QA) of CT simulators consists of procedures for QA of (1) CT scanner, (2) CT simulation software, and (3) QA of the overall process. Several publications have addressed QA needs for CT scanners and CT simulators^{11, 12, 19, 20, 27, 32, 34, 39-51}. The American Association of Physicist in Medicine (AAPM) Task Group 66 has been charged with addressing the QA process for CT simulation. The task group is currently in the process of preparing a comprehensive document that will address all of the above-mentioned QA procedures. The goals of the quality assurance program should be concentrated on the imaging performance and mechanical integrity of the CT scanner, accuracy of the virtual simulation software in reconstruction of the

virtual patient and treatment machine and other functions²⁷, and the overall correct positioning and treatment of the patient. As often suggested by the AAPM^{20, 39}, the QA procedures are separated into daily, weekly, monthly, quarterly, and annual procedures. The frequency of a QA task depends on its significance for the overall program accuracy and reliability and other factors (past performance, etc.)²⁰. Tolerance and action levels for various components of the QA program depend on the institutional policies and national and international organization recommendations^{20, 27, 39} and current standard of practice.

If the CT scanner is located within the radiation oncology department, establishment of a well-designed QA program should not be a problem. In a situation where the CT scanner is located outside the radiation oncology department, establishment and overseeing of an appropriate QA program may be somewhat harder to do. If the equipment is shared with another department it is the responsibility of the CT simulation team (physician, medical physicist, administration) to ensure that the CT scanner QA program satisfies the needs of the virtual simulation process, that the QA is performed at specified intervals, and that specified action levels are followed. It is very important that proper communication channels be established with all users of a shared CT scanner so that any changes or modifications in the scanner operation and performance can be notified and explained to all users. Radiation oncology personnel do not necessarily have to perform the actual QA of an outside scanner but should at minimum understand the QA procedures and review QA records at routine intervals.

Quality assurance of CT scanners: The AAPM Report Number 39, "Specification and acceptance testing of computed tomography scanners"³⁹ has describe in great detail acceptance testing and QA procedures for CT scanners. Several other references have been published that address this issue^{12, 40, 44-46}. Also a good source of information is the www.impactscan.org website. Until publication of the AAPM TG66 report, the above referenced documents can be used for designing a CT simulator QA program. The QA Program should address radiation safety, CT scanner dosimetry,

electromechanical performance, x-ray generator operation, and imaging performance.

Quality assurance of the CT simulation software: The QA of the virtual simulation software is in many aspects similar to QA procedures for 3D treatment planning systems as many functions and features are common to these two types of software. The AAPM TG53 report "Quality assurance for clinical radiotherapy treatment planning²⁷" has addressed in detail the QA needs for clinical radiation oncology treatment planning. This document can be applied when designing a virtual simulation software QA program. Additionally, the AAPM TG66 will address QA issues more specific to virtual simulation. The QA should include verification of spatial and geometric accuracy of the software (contour delineation, isocenter localization, treatment port definition, virtual treatment machine operation, etc.), evaluation of DRRs and DCRs, and accuracy of the multimodality image fusion and registration process. .

V. CONCLUSIONS

CT simulation process has made significant improvements over the past ten years due to advances in CT scanner technology and constant increase in computer abilities. Virtual simulation has gone from a concept practiced at few academic centers to several available sophisticated commercial system located in hundreds of radiation oncology departments around the world. The concept has been embraced by the radiation community as a whole. This acceptance of virtual simulation comes from improved outcomes and increased efficiency associated with conformal radiation therapy. Imaged based treatment planning is necessary to properly treat a multitude of cancers and CT simulation is a key component in this process. Due to demand for CT images, CT scanners are being placed directly in radiation oncology departments. In our radiation oncology center, two dedicated CT simulators are used and a large number of our patients are scanned using MR and PET scanners located in the diagnostic radiology department. As CT technology and computer

power continue to improve so will the simulation process and it may no longer be based on CT alone. CT/PET combined units are commercially available and could prove to be very useful for radiation oncology needs. Several authors have described MR Simulators where the MR scanner has taken the place of the CT scanner. It is difficult to predict what will happen over the next ten years, but it is safe to say that image-based treatment planning has much more to offer. Image-based treatment planning is one of the great research avenues with tremendous opportunities for improved patient care.

REFERENCES

1. Goitein M, Abrams M. Multi-dimensional treatment planning: I. Delineation of anatomy. *Int J Radiat Oncol Biol Phys*,9:777-787,1983.
2. Goitein M, Abrams M, Rowell D, Pollari H, Wiles J. Multi-dimensional treatment planning: II. Beam's eye-view, back projection, and projection through CT sections. *Int J Radiat Oncol Biol Phys*,9:789-797,1983.
3. Sherouse GW, Novins K, Chaney EL. Computation of digitally reconstructed radiographs for use in radiotherapy treatment design. *Int J Radiat Oncol Biol Phys*,18:651-658,1990.
4. Sherouse G, Mosher KL, Novins K, Rosenman EL, Chaney EL. Virtual Simulation: Concept and Implementation." In: Bruinvis IAD, van der Giessen PH, van Kleffens HJ, Wittkamper FW, editors. Ninth International Conference on the Use of Computers in Radiation Therapy: North-Holland Publishing Co.); 1987. p. 433-436.
5. Sherouse GW, Bourland JD, Reynolds K. Virtual simulation in the clinical setting: some practical considerations. *Int J Radiat Oncol Biol Phys*,19:1059-1065,1990.
6. Nagata Y, Nishidai T, Abe M, Takahashi M, Okajima K, Yamaoka N, et al. CT simulator: a new 3-D planning and simulating system for radiotherapy: Part 2. Clinical application [see comments]. *Int J Radiat Oncol Biol Phys*,18:505-513,1990.
7. Nishidai T, Nagata Y, Takahashi M, Abe M, Yamaoka N, Ishihara H, et al. CT simulator: a new 3-D planning and simulating system for radiotherapy: Part 1. Description of system [see comments]. *Int J Radiat Oncol Biol Phys*,18:499-504,1990.
8. Perez CA, Purdy JA, Harms W, Gerber R, Matthews J, Grigsby PW, et al. Design of a fully integrated three-dimensional computed tomography simulator and preliminary clinical evaluation. *Int J Radiat Oncol Biol Phys*,30:887-897,1994.
9. Curry TS, Dowdey JE, Murry RC. *Computed Tomography*. Christensen's Physics of Diagnostic Radiology. 4th ed. Malvern, Pennsylvania: Lea & Febiger; 1990. p. 289-322.
10. Kalender WA, Polacin A. Physical performance characteristics of spiral CT scanning. *Med Phys*,18:910-915,1991.
11. Kalender WA, Polacin A, Suss C. A comparison of conventional and spiral CT: an experimental study on the detection of spherical lesions [published erratum appears in *J Comput Assist Tomogr* 1994 Jul-Aug;18(4):671]. *Journal of computer assisted tomography*,18:167-176,1994.
12. Van Dyk J, Taylor, J.S. CT-Simulators. In: Van Dyk J, editor. *The Modern Technology for Radiation Oncology: A Compendium for Medical Physicist and Radiation Oncologists*. Madison, WI: Medical Physics Publishing; 1999. p. 131-168.
13. Kalender WA, Seissler W, Klotz E, Vock P. Spiral volumetric CT with single-breath-hold technique, continuous transport, and continuous scanner rotation. *Radiology*,176:181-183,1990.

14. Fuchs T, Kachelriess M, Kalender WA. Technical advances in multi-slice spiral CT. *Eur J Radiol*,36:69-73,2000.
15. Klingenbeck_Regn K, Schaller S, Flohr T, Ohnesorge B, Kopp AF, Baum U. Subsecond multi-slice computed tomography: basics and applications. *Eur J Radiol*,31:110-124,1999.
16. Hu H. Multi-slice helical CT: scan and reconstruction. *Med Phys*,26:5-18,1999.
17. Butker EK, Helton DJ, Keller JW, Crenshaw T, Fox TH, Elder ES, et al. Practical Implementation of CT-Simulation: The Emory Experience. In: Purdy JA, Starkschall G, editors. *A Practical Guide to 3-D Planning and Conformal Radiation Therapy*. Middleton, WI: Advanced Medical Publishing; 1999. p. 58-59.
18. Conway J, Robinson MH. CT virtual simulation. *british journal of radiology*,70 Spec No:S106-118,1997.
19. Garcia-Ramirez JL, Mutic S, Dempsey JF, Low DA, Purdy JA. Performance evaluation of an 85 cm bore x-ray computed tomography scanner designed for radiation oncology and comparison with current diagnostic CT scanners. *Int J Radiat Oncol Biol Phys*, Submitted for publication, Jun, 2001.
20. Kutcher GJ, Coia L, Gillin M, Hanson WF, Leibel S, Morton RJ, et al. Comprehensive QA for radiation oncology: report of AAPM Radiation Therapy Committee Task Group 40. *Med Phys*,21:581-618,1994.
21. Nowak B, Di_Martino E, Janicke S, Cremerius U, Adam G, Zimny M, et al. Diagnostic evaluation of malignant head and neck cancer by F-18-FDG PET compared to CT/MRI. *Nuklearmedizin*,38:312-318,1999.
22. Slevin NJ, Collins CD, Hastings DL, Waller ML, Johnson RJ, Cowan RA, et al. The diagnostic value of positron emission tomography (PET) with radiolabelled fluorodeoxyglucose (18F-FDG) in head and neck cancer. *J Laryngol Otol*,113:548-554,1999.
23. Torre W, Garcia_Velloso MJ, Galbis J, Fernandez O, Richter J. FDG-PET detection of primary lung cancer in a patient with an isolated cerebral metastasis. *Int J Radiat Oncol Biol Phys*,41:503-505,2000.
24. Kessler ML, Pitluck S, Petti P, Castro JR. Integration of multimodality imaging data for radiotherapy treatment planning. *Int J Radiat Oncol Biol Phys*,21:1653-1667,1991.
25. Ling CC, Humm J, Larson S, Amols H, Fuks Z, Leibel S, et al. Towards multidimensional radiotherapy (MD-CRT): biological imaging and biological conformality. *Int J Radiat Oncol Biol Phys*,47:551-560,2000.
26. Chao KS, Bosch WR, Mutic S, Lewis JS, Dehdashti F, Mintun MA, et al. A novel approach to overcome hypoxic tumor resistance: Cu-ATSM-guided intensity-modulated radiation therapy. *Int J Radiat Oncol Biol Phys*,49:1171-1182,2001.
27. Fraass B, Doppke K, Hunt M, Kutcher G, Starkschall G, Stern R, et al. American Association of Physicists in Medicine Radiation Therapy Committee Task Group 53: quality assurance for clinical radiotherapy treatment planning. *Med Phys*,25:1773-1829,1998.
28. Chaney EL, Thorn JS, Tracton G, Cullip T, Rosenman JG, Tepper JE. A portable software tool for computing digitally reconstructed radiographs. *Int J Radiat Oncol Biol Phys*,32:491-497,1995.
29. Jacky J, Kalet I, Chen J, Coggins J, Cousins S, Drzymala R, et al. Portable software tools for 3D radiation therapy planning. *Int J Radiat Oncol Biol Phys*,30:921-928,1994.
30. Drzymala RE, Holman MD, Yan D, Harms WB, Jain NL, Kahn MG, et al. Integrated software tools for the evaluation of radiotherapy treatment plans. *Int J Radiat Oncol Biol Phys*,30:909-919,1994.
31. Van Dyk J, Mah, K. Simulation and Imaging for Radiation Therapy Planning. In: Williams JRaT, T.I., editor. *Radiotherapy Physics in Practice*. Second ed. Oxford, England: Oxford Univeristy Press; 2000. p. 118-149.
32. Coia LR, Schultheiss TE, Hanks G, editors. *A Practical Guide to CT Simulation*. Madison, WI: Advanced Medical Publishing; 1995.
33. Bahner ML, Debus J, Zabel A, Levegrun S, Van Kaick G. Digitally reconstructed radiographs from abdominal CT scans as a new tool for radiotherapy planning. *investigative radiology*,34:643-647,1999.
34. McGee KP, Das II, Sims C. Evaluation of digitally reconstructed radiographs (DRRs) used for clinical radiotherapy: a phantom study. *Med Phys*,22:1815-1827,1995.
35. Yang C, Guiney M, Hughes P, Leung S, Liew KH, Matar J, et al. Use of digitally reconstructed radiographs in radiotherapy treatment planning and verification. *Australas Radiol*,44:439-443,2000.
36. Butker EK, Helton DJ, Keller JW, Hughes LL, Crenshaw T, Davis LW. A totally integrated simulation technique for three-field breast treatment using a CT simulator. *Med Phys*,23:1809-1814,1996.
37. Mah K, Danjoux CE, Manship S, Makhani N, Cardoso M, Sixel KE. Computed tomographic simulation of craniospinal fields in pediatric patients: improved treatment accuracy and patient comfort. *Int J Radiat Oncol Biol Phys*,41:997-1003,1998.
38. Jani SK, editor. *CT Simulation for Radiotherapy*. Madison, WI: Medical Physics Publishing; 1993.
39. AAPM RN. *Specification and Acceptance Testing of Computed Tomography Scanners*. New York: American Institute of Physics; 1993.
40. Alexander J, Kalender W, Linke G. *Computed Tomography: Assurance Criteria, CT System Technology, Clinical Applications*. Chichester: Wiley; 1986.
41. Bel A, Bartelink H, Vijlbrief RE, Lebesque JV. Transfer errors of planning CT to simulator: a possible source of setup inaccuracies? *Radiother Oncol*,31:176-180,1994.
42. Cacak RA, Hendee RR. Performance evaluation of a fourth-generation computed tomography (CT) scanner. *Proc Soc Photo-Optical Instrum Eng*,173:194-207,1979.
43. Craig TC, Brochu D, Van Dyk J. A quality assurance phantom for three-dimensional radiation treatment planning. *Int J Radiat Oncol Biol Phys*,1999.
44. Gerber RL, Purdy JA. Quality assurance procedres and performance testing for CT-simulators. In: Purdy JA, Starkschall G, editors. *A Practical Guide to 3-D Planning and Conformal Radiation Therapy*. Middleton, WI: Advanced Medical Publishing, Inc.; 1999. p. 123-132.
45. Loo D, editor. "CT Acceptance Testing." In *Specification, Acceptance Testing and Quality Control of Diagnostic X-ray Imaging Equipment*. New York: American Institute of Physics; 1991. Seibert JA, Barnes GT, Gould RG, editors. *Proceedings of AAPM Summer School*.
46. McGee KP, Das II. Commissioning, acceptance testing, and quality assurance of a CT simulator. In: Coia LR, Schultheiss TE, Hanks GE, editors. *A practical guide to CT simulation*. Madison, WI: Advanced Medical Publishing; 1995. p. 39-50.
47. Mutic S, Dempsey JF, Bosch WR, Low DA, Drzymala R, Chao KS, et al. Multimodality image registration quality assurance for conformal three-dimensional treatment planning. *Int J Radiat Oncol Biol Phys*, In press, 2001.
48. Polacin A, Kalender WA, Brik MA, Vannier MA. Measurement of slice sensitivity profiles in spiral CT. *Med Phys*,21:133-140,1994.
49. Polacin A, Kalender WA, Marchal G. Evaluation of section sensitivity profiles and image noise in spiral CT. *Radiol*,185:29-35,1992.
50. Poletti JL. An ionization chamber-based CT scanner dosimetry. *Phys Med Biol*,29:725-731,1984.
51. Spokas JJ. Dose descriptors for computed tomography. *Med Phys*,9:288-292,1982.