

VIRTUAL SIMULATION FOR RADIATION THERAPY TREATMENT USING CT MEDICAL DATA

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Abstract

Simulators are medical devices used in the oncology clinics to perform the simulation for the external beam radiotherapy treatment. Unlikely for a clinic to obtain a real Simulator is a high investment in terms of money, space and personnel. The alternative here can be a Virtual Simulator (VS). The CT simulators are system-software that can perform the simulation process using the Computed Tomography (CT) data set of the patient, including the external patient's skin landmarks, instead of the physical patient. In this paper, a new high performance CT based virtual simulation system running on a low cost widely available PC hardware – EXOMIO would be presented. The implemented high-end visualization techniques allow the users to simulate every function of the real simulator including the mechanical component movements, radiation beam projection and fluoroscopy.

1 INTRODUCTION

Radiation therapy (RT) uses high-energy photon rays in order to deliver a very accurate dose of radiation to a well-defined target volume with minimal damage to surrounding healthy tissues. The desired result is the eradication of the disease and the improvement or prolonging of patient's life. RT is a very demanding process that requires accuracy and effectivity. The RT process is composed of several steps. One important step in this process is *simulation*. Simulation provides localization of the target volume, the area that will receive the maximum amount of dose, and delineation organ at risk, the volumes and organs that must receive the minimum dose. Once these structures have been well defined, the next step is the definition of the irradiation fields in relation with the target volume and the organs at risk. During treatment, the patients receive their therapy via a number of fractions. Therefore, there must be a confirmation that the irradiation orientation and the structure localization remain unchanged. One of the significant technological advances in radiation oncology in the past 20 years is the implementation of CT-based virtual simulation in the clinical routine. The concept, often termed CT-Sim virtualises the simulation process that is performed on a conventional simulator. The patient is scanned on the CT device together with

localization-reference markers made from radio-opaque material (e.g. aluminium), which are attached on the patient's skin. The volumetric CT data are directly transferred to the CT-Sim via the local network of the clinic. This work describes a new CT based virtual simulator system, EXOMIO¹, that has been developed at Fraunhofer IGD in collaboration with Städtisches Klinikum Offenbach, department for radiation therapy, and is now used in clinical practice already at several institutes worldwide. Its main advantages are: (a) it is based on low cost and widely available hardware (PC), unlike the other commercially available systems that depend on expensive workstations, (b) it provides high quality and high performance visualization tools and (c) it can be connected via network to any DICOM supporting CT or MR scanner and via DICOM-RT supplements it enables support for treatment planning system and verification system at linear accelerators.

2 METHODS AND MATERIALS

2.1 Principle of Computer Tomography (CT)

Computer Tomography is a technology that allows the non-destructive evaluation of the internal structure of the objects. Since a lot of year this technique has been used successfully in medicine and material testing to examine local differences in density by generating images of different cutting planes of the object concerned. The basics of CT imaging are that of x-ray principles.

When x-rays pass through a patient's body and are absorbed, they in turn create a profile of x-rays beams. The profiles are stored on files which to state basically creates an image. For CT imaging the film is substituted by a detector, which measures the x-ray profile. The CT scanner consists of a gantry, which includes the x-ray source, x-ray detectors, and data acquisition system, a patient table, a control console and a computer.

The CT is linked to the computer. The scanner rotates about the patient, this proceeds as it takes pictures or slices of tissue. The images in general are then processed by the computer and either depicted on a cathode-ray tube and screen or are saved a permanent location on film. The resulted image is displayed or saved and referred to as CT slices. More specifically, as the image is being acquired,

¹ MedInTec GmbH, Bochum, Germany

the detector is making a 360-degree rotation. During the rotation the detector takes numerous snapshots (profiles) of the attenuated x-ray beam. The CT images are reconstructed from a large number of measurements of x-ray transmission through the patient. This projection data are used to reconstruct the CT image (Figure 1). Figure 2 shows an slice from an x-ray CT in the heart lung area.

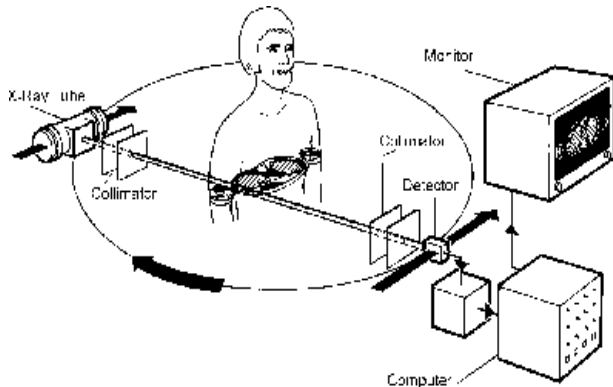


Figure 1. Principle of the X-ray CT scanner

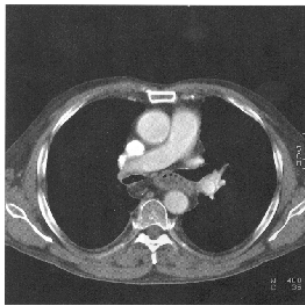


Figure 2. X-Ray CT slice showing heart and lungs

2.2 Workflow Concept

The affect of the radiotherapy treatment is based on the precise delivery of high irradiation dose on the tumor site without damaging the surrounding healthy tissues. Therefore patient positioning, target volume definition and irradiation field placement are vary critical steps while planning the irradiation process. Briefly in the current clinical routine using, the patient goes through the following steps (Figure 3):

1. Localize area to be irradiated on the Simulator
2. Collect patient's CT data including attached aluminium markers.
3. Transfer CT data to treatment planning system (TPS), where physicians perform the tumour volume definition. In this step the physicist will define the organs at risk, will place the necessary fields to perform the specific treatment technique and she/he will calculate the dose distribution around the tumour area and the organs at risk.
4. The treatment plan parameters will by verified on the real Simulator.
5. Verify patient position on (Linear Accelerator) LINAC before irradiation.

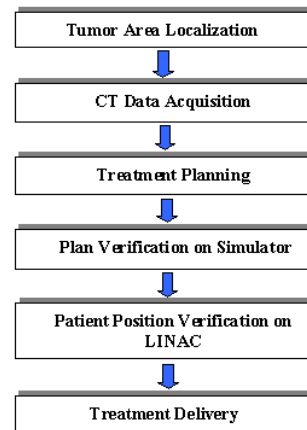


Figure 3. Current clinical routine for external beam treatment delivery.

One of the significant technological advances in radiotherapy in the past 20 years is the implementation of CT or Virtual Simulators (VS), in the clinical routine. Sherouse in 1987 [1] first proposed the concept, often termed CT-Sim to distinguish it from Sim-CT where a simulator is modified for CT use and by the late 1990s several designs and clinical assessments of CT virtual simulators have been reported [1-8]. Using VS, the clinical routine is modified accordingly (Figure 4) [9,10]:

1. Collect patient's CT data including attached aluminium markers.
2. Transfer CT data to VS. The physician defines the tumour volume and the organs at risk and she/he will place the necessary fields relative to the tumour volume.
3. The simulation plan and the CT data are transferred via DICOM (Digital image and Communication in Medicine) server to the TPS for dose calculation and final treatment plan optimization.
4. Verify patient position on LINAC before irradiation.
5. Perform treatment on the treatment machine (Linear Accelerator or LINAC).

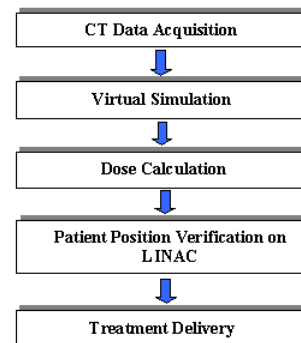


Figure 4. Current clinical routine for external beam treatment delivery.

Considering the above steps, one can evaluate the importance of the communication requirements of a CT-

Sim. In EXOMIO the philosophy of the stand-alone CT-Sim system is adapted. In practice, the system is capable to interface any CT scanner device and any treatment planning system through DICOM communication protocol. The DICOM—protocol is used for communicating digital images from the medical imaging modalities, and the DICOM-RT supplements to communicate structures and beam data to/from the treatment planning systems and verification systems. All datasets can be stored in the EXOMIO server and one can access them from any client installed on the local network of the institution.

2.3 Main System Features

The main system features can be separated into several categories including visualization features, volume definition tools, treatment field design, patient set-up and simulation plan documentation. In this paper only a small part of the visualization capabilities will be presented.

EXOMIO has the ability to generate 2D and 3D images using only the original CT data of the patient. The 2D images displayed are the original axial CT, MR or PET. Multi planar reconstructions (MPR) can be generated in real time in the orthogonal, coronal and sagittal directions, and any oblique direction. The 3D reconstructed images are a must in CT-Sim systems in order to simulate the patient anatomy and the images generated from the real simulator or the treatment machine. The first layout contains four windows and the displayed images are the Beam's Eye View (BEV), the Observer's Eye View (OEV) and the Room View (RM), together with the axial slices. The second layout is composed again of four windows, containing the three orthogonal slice directions and the OEV. This layout is ideal for navigation through the CT volume, for volume delineation and to observe complex radiation field arrangements. The last layout contains every image described above. This layout has six windows emphasizing the size of the BEV image, since the physicians feel comfortable working with this image. In both rendering views, OEV and BEV, the volume orientation is controlled using a mouse track-ball. The user simply clicks-and-rotates the patient's volume to any viewing angle. The same principle is used with the BEV image but in this case only the rotations of gantry and table are possible.

EXOMIO can use large amounts of data, from 40 up to 300 slices, in order to produce high quality anatomical images. This system enables reading of CT data, acquired not only with a single slice CT scanner (such as a Siemens SOMATOM Plus 4), but also multi-slice data ranges, acquired in this study with four slices (SOMATOM Volume Zoom). EXOMIO can be connected via network directly to any CT scanner that support DICOM protocol. The system allows the adaptation to any LINAC configuration through a machine configuration module that is designed according to the international standard for radiotherapy equipment (IEC 1217). This configuration involves limitation on

movements of the mechanical component and description of the component's dimensions (e.g., multileaf collimator, or MLC) (Figure 5).

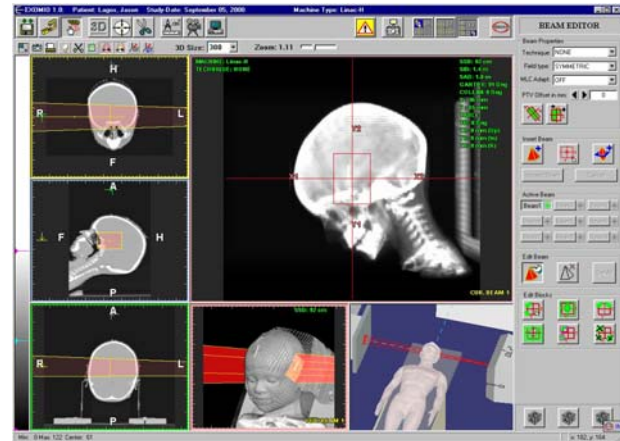


Figure 5. The six-window layout of EXOMIO. On the left side the slices windows, the middle lower window is the OEV, the lower right the Room View and the upper right hosts the BEV.

2.4 Volume Visualisation

3D image reconstruction using volume rendering is the most essential component, the “heart” actually, of a CT-Sim system. The 3D reconstruction of complete patient anatomy for different anatomical sites is of great benefit for the clinicians. Only a small part of the patient's anatomy can be visualized on the conventional simulator during fluoroscopy mode, a drawback that comes due to the limited size of the detection surface of the image intensifier.

The rendering pipeline used in EXOMIO is based on the work of G.Sakas [13]. In BEV we use perspective projection and in the OEV parallel projection but both views support the same illumination models: transparent mode using maximum intensity projection (MIP) [14], X-ray [11], and surface reconstruction mode using iso-value, gradient [12] and semi-transparent. In both illumination models, surface and transparent, one can visualize selected tissue ranges using linear or triangle look-up table. The volume-rendering pipeline is based on the widespread ray-casting algorithm. In other words the rendering process can be spread when more than one processor are available on the hardware. Additional important factors for the reconstruction speed of the final image are the data set size and the size of the final 3D image, which influence the number of rays used during volume reconstruction. Nevertheless, in practice the 3D images in EXOMIO can be calculated almost in real time. The most common image presented in the CT-Sim systems is the virtual X-ray image generated from digital CT or MR volumes. These images are often called the digitally reconstructed radiographs (DRRs). The term DRR is used when we refer to those X-Ray images that are generated with an unrealistic way using direct volume

rendering techniques or to those images that are generated from volume data using a better approximation of the physical model. In both cases we try to simulate the attenuation of the X-ray through the digital patient's body. The manipulation of tissue properties like the mass attenuation coefficient, assist the generation of unique images simulating physical principles of radiographic imaging. The most common example is the generation of mega-voltage DRR images for direct comparison with the portal images. In addition DRR images provide unique anatomical information to the clinicians that no conventional X-ray device can produce. An example of different X-ray reconstruction modes is illustrated in Figure 6.

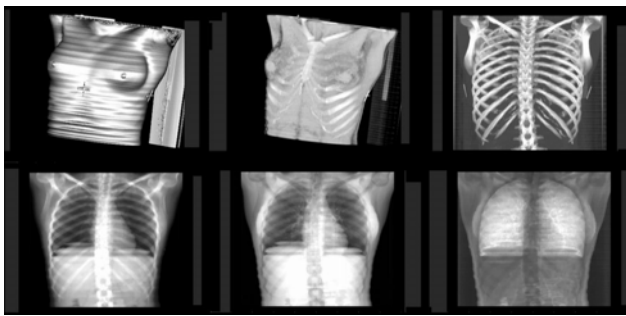


Figure 6. Volume rendering modes supported from EXOMIO. On the top row from left to right: isovalue mode, semitransparent mode and maximum intensity projection. On the lower row X-ray images reconstructed using different tissue ranges. From left to right: full tissue range, muscle tissues and lung tissues.

Another type of 3D image with high importance in CT simulation is the external body surface anatomy. High-resolution volumetric CT data in combination with volume rendering techniques can produce a very accurate representation of 3D patient anatomy. This concept is extremely suitable for assessing the configuration of the radiation beam in three dimensions. EXOMIO supports the visualization of the irradiation beam and block arrangement as 3D semitransparent objects. In addition the light field projection of the radiation field, delineated or not, can be simulated and manipulated in real time during field rearrangement or shielding block-contour design (Figure 7).

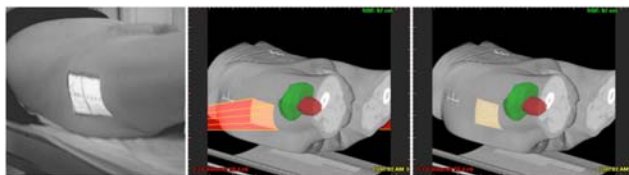
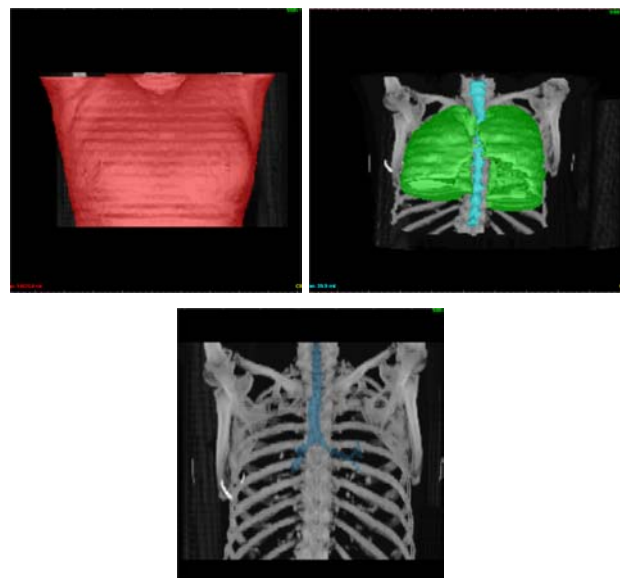


Figure 7. The light field projection on patient's skin (left). 3D beam object reconstructed with patient's CT data (middle). Virtual light field projection on patient's surface.

2.5 Volume Definition Tools

Target volume and critical structure definition is a complex and time-consuming process in radiotherapy. The complexity varies for different anatomic sites. In CT-simulation and plan evaluation, both the physicists and radiation oncologists interact closely to subjectively identify the plan most appropriate for the individual patient. In order to reduce the investment of time and effort by the radiation oncology staff, several image analysis tools are integrated. The system allows the user to draw contours around the tumour, target, and normal tissues on a slice-by-slice basis and provides, at the same time, a cross-reference to planar images.

A function that significantly accelerates the contouring process is the linear interpolation between the original key-contours. The same principle can be applied for defining structures in both planar planes, sagittal and coronal. The contour edit functions allow the user to move, scale and rotate an entered contour in addition to providing tools for rapid contour corrections and copying to inferior and posterior slice. Organs with large differences in their intensities can be segmented semi-automatically. In terms of user effort the only action required from the user is the selection of an initiation point for the algorithm on the original axial slices. The complete 3D geometry of the organ will be traced automatically. Some of the common organs with high sensitivity factor and vital importance are the lungs, the spinal cord and the trachea [15-19]. In addition to those organs, the external body contour can be extracted in a similar manner. The contours that are generated semi-automatic can be manipulated and modified at the same manner as those defined manually. The user has the possibility to reconstruct the segmented organs as volumetric structures on the BEV and OEV images. Figure 8 illustrates different 3D reconstruction examples of segmented structures.



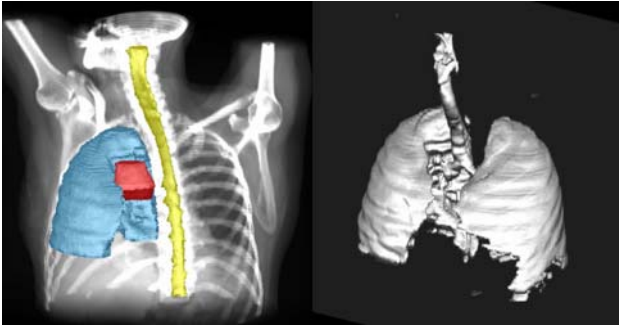


Figure 8: 3D segmentation images for different organs : Skin, Lungs and Spinal canal, Bronchus, Spinal canal and Lungs with left lung and tumour, Spinal canal and Lungs (different view).

3 RESULTS

One example of the use of EXOMIO in clinical practice would be presented. The patient is a 75 years old patient with stage T3N0M0 cancer of the prostate. The radiation fields cover the entire prostate glands, which includes safety margins. For this case, CT slices of 3mm thickness and 3mm slice distance have been reconstructed using spiral CT acquisition from a 512x512 pixel matrix.

Figure 9 shows the clinical target volume (CTV) delineation procedure. EXOMIO offers the possibility to contour the CTV in at least three planes (one sagittal, one coronal and at least one axial CT plane) and it automatically extracts the 3D CTV. The physician can then do fine contour corrections if necessary. After the CTV is validated the physicians decide the appropriate clinical margins. In this prostate case anisotropic margin of 10 mm in the lateral, 10 mm in the cranio-caudal and 0 mm in the ventro-dorsal axes have been used.

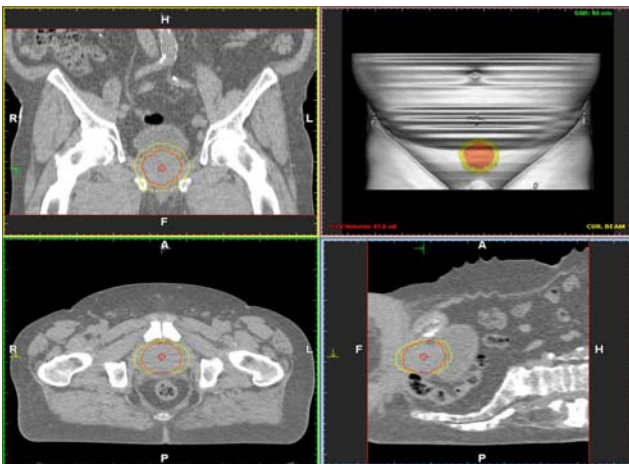


Figure 9: Automatic extraction of PTV from delineated CTV in EXOMIO by applying user defined clinical margins. The extracted PTV and CTV are shown in different colours in the three major planes and in the OEV (3D).

In figure 10 an oblique cut in the OEV window is shown and is used for the validation of the field configuration through the 3D patient volume. Figure 8 demonstrates the overall 3D nature of the EXOMIO simulator. This includes the addition of a fifth field, which is non-coplanar to the four fields in the box-technique.

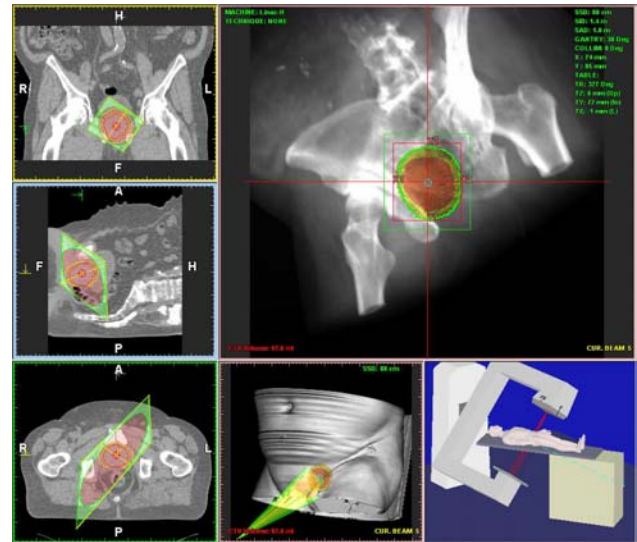


Figure 10: Planning of an additional fifth beam non-coplanar to the four fields of the box-technique. (Top left) Coronal plane. (Centre left) Sagittal plane. (Bottom left) CT slice with the fifth field. (Top right) DRR for the new field with the automatically on PTV adapted block: irregular field. (Bottom centre) OEV showing the patient, the beam cone and the light field projection on the skin for the fifth field and the 3D PTV. (Bottom right) 3D room view of the virtual simulator and patient.

4 DISCUSSION

The advantages of CT-based virtual simulation are well known and include the fact that target volumes, critical organs and structures can be effectively defined and displayed in multiple image planes (axial, coronal, sagittal or oblique). Improved manual and automated contouring tools greatly simplify normal critical structure, tumour, and target volume delineation. A direct interface to the treatment planning system permits efficient virtual verification. In CT-Sim it is possible to display more information on the same screen such as: (a) the beam's eye-view, where the Digital Reconstructed Radiograph is displayed, (b) the room view including a 3D model of the simulator or the treatment machine and (c) the observer's eye-view, where the 3D surface reconstruction of the patient is shown. These images offer the user an overview of the simulation and treatment planning process. Furthermore, in virtual simulation one can observe larger parts of the patient's volume than on the conventional simulator where fluoroscopy is limited by the dimensions

of the image intensifier (detector). According to our clinical experience the CT-Sim system could simulate all of the treatment cases, replacing completely the real simulator. The CT-Sim system has been easily integrated into our clinical radiotherapy routine. The modification required in the CT room was the installation of the laser marking system for the registration of the treatment reference point, similar to the installation in the LINAC room. In addition, the flat CT table-top had to replace the original curved table-top.

Visualization of multileaf collimator (MLC) field is only possible with CT-Sim and this is most important because of widespread use of MLCs. CT-Sim also makes it possible, without the patient needing to be recalled, for verification to be repeated after changes to the treatment plan. Indeed, CT-Sim may eliminate the requirement for a conventional simulator for several treatment sites. All the main features of a classical simulator are available, software based, in EXOMIO. The validation of beam geometries in a classical simulator is only based on X-ray contrast between tissues of different densities such as bone, lung or a contrast filled organ such as the bladder. In particular CT based simulation enables accurate delineation of multi-field geometries, all necessary field matching and multi-planar field adaptation as shown in our results. These functions are not possible with classical simulation. In addition the CT based virtual simulation brings benefit for patient scheduling because it avoids the often experienced *bottlenecks* in patient workload flow within a department of radiation oncology. Finally 3D visual representation of the particular organ, in addition with the clinical examinations, could be a powerful tool to the doctors for diagnosis, medical treatment or surgery.

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