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Virtual CT-3D simulation using EXOMIO: with special reference to prostate cancer

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The paper describes a new CT based 3D virtual simulator system called EXOMIO that has been developed at the Institut für Graphische Datenverarbeitung [Fraunhofer IGD] in collaboration with the Department of Radiation Oncology of the Klinikum Offenbach. The system is based on low cost and widely available hardware [PC]: unlike the other commercially available systems that depend on expensive workstations. It provides high quality and high performance visualisation tools. It can be connected via a network to any DICOM supporting CT or MR scanner and via DICOM-RT supplements it enables support for a treatment planning system and for a verification system for linear accelerators. Finally, a prostate cancer case history is given as an example of a clinical application of EXOMIO.

Symulacja wirtualna z zastosowaniem systemu EXOMIO – przydatność u chorych z nowotworami gruczołu krokowego

W pracy przedstawiono nowy system symulacji, oparty na obrazach tomografii komputerowej. System ten, zwany EXOMIO, został opracowany w Institut für Graphische Datenverarbeitung [Fraunhofer IGD] we współpracy z Zakładem Radioterapii Nowotworów Klinikum Offenbach. Podstawowa zaleta systemu EXOMIO to wykorzystywanie taniego, szeroko dostępnego oprogramowania (w odróżnieniu od systemów konkurencyjnych, wymagających kosztownego oprogramowania). Dodatkowo EXOMIO zapewnia doskonałą wizualizcję i może być, przez sieć, połączony z pracującym w systemie DICOM skanerem MRI lub CT, co ułatwia planowanie leczenia i pozwala zweryfikować systemy akceleratorów liniowych.
Kliniczne zastosowanie systemu EXOMIO przedstawiono na przykładzie chorego z rakiem prostaty.

Key words: virtual simulation, radiotherapy, CT-3D imaging, EXOMIO
Słowa kluczowe: symulacja wirtualna, radioterapia, rak prostaty

Introduction

The radiation therapy process

The field of radiation oncology includes the use of high energy photons to deliver an accurate dose of radiation to a well defined target volume whilst minimising damage to surrounding healthy tissues. The objective is the eradication of the cancer, improvement in the patient's subsequent quality of life and the prolongation of their survival.

The entire radiation therapy process is composed of several parts and one important step is simulation. This encompasses localisation of the target volume and the delineation of organs and normal healthy tissue which could be at risk if they are over-irradiated. Then, once these structures have been well defined, the next step leads to the description of the radiation fields in relation to the target volume and these structures. During radiation treatment the patients receive their therapy *via* a number of fractions. Hence there must be confirmation that the orientation of the radiation fields and also the localisation of the critical structures remains unchanged.

CT-Sim & Sim-CT

One of the significant technological advances in radiation oncology in the past 20 years is the implementation within the clinical routine of CT based virtual simulation. The

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concept, often termed CT-Sim [to distinguish it from Sim-CT where a simulator is modified for CT use] was first proposed by Sherouse *et al* in 1987 [1]. By the late 1990s several designs and clinical assessments of CT virtual simulators had been reported [2-20].

The CT-Sim concept

The CT-Sim concept is based on the use of digital data relating to the patient, mainly CT slices, and does not require the physical presence of the patient: hence the term *virtual*. Basically the CT-Sim process virtualises the conventional simulation process that is performed using a standard X-ray simulator. With CT-Sim the patient is scanned on the CT scanner with localisation reference markers made from radio-opaque material: for example aluminium attached on the patient's skin. The volumetric CT data are directly transferred to the CT-Sim virtual simulator *via* the local network of the radiation oncology clinic.

Material and methods

Workflow pattern

The functional steps of the CT-Sim system within the overall framework of the process of the radiation treatment planning which precedes the treatment delivery are illustrated in the summary block diagram in Figure 1.

Firstly it is necessary to collect the patient's CT data, including that relating to any attached aluminum markers for use as reference points. To integrate a CT scanner within the radiotherapy clinical routine, it was necessary to modify our table top from a curved top to a flat top. This was in order to have a table top which was identical to that of the linear accelerator and therefore ensure the same geometry for the patient's anatomy during treatment planning *and* treatment delivery.

Secondly the CT data must be transferred to the CT-Sim so that the physician can define the tumour volume [PTV] and the organs at risk [OAR]. In addition, the necessary treatment fields will be initially positioned relative to the PTV.

Thirdly, after performing the CT-Sim process described above, there are two potential directions which can be followed. [*A*] For simple treatment fields, such as for palliative treatments, the data communication through the Treatment Planning System [TPS] may be avoided. Instead, the simulation plan can be applied *via* a movable laser device for external patient field marking. [*B*] For 3D treatment where more sophisticated planning of the treatment is required, the simulation plan, the delineated structures and the CT data are transferred *via* DICOM server to the TPS for dose calculation and for the final treatment plan optimization.

Fourthly, the patient is registered in the treatment position using the laser marking system. The original reference point that was placed on the CT device is recovered at this point. *Fifthly*, the treatment parameters from the treatment machine [usually a linear accelerator] are applied to the treatment plan. This step is essential before, for example, the monitor units for a given field are calculated. *Sixthly,* the treatment parameters and patient position are verified with the help of portal imaging. *Finally*, the treatment is delivered.

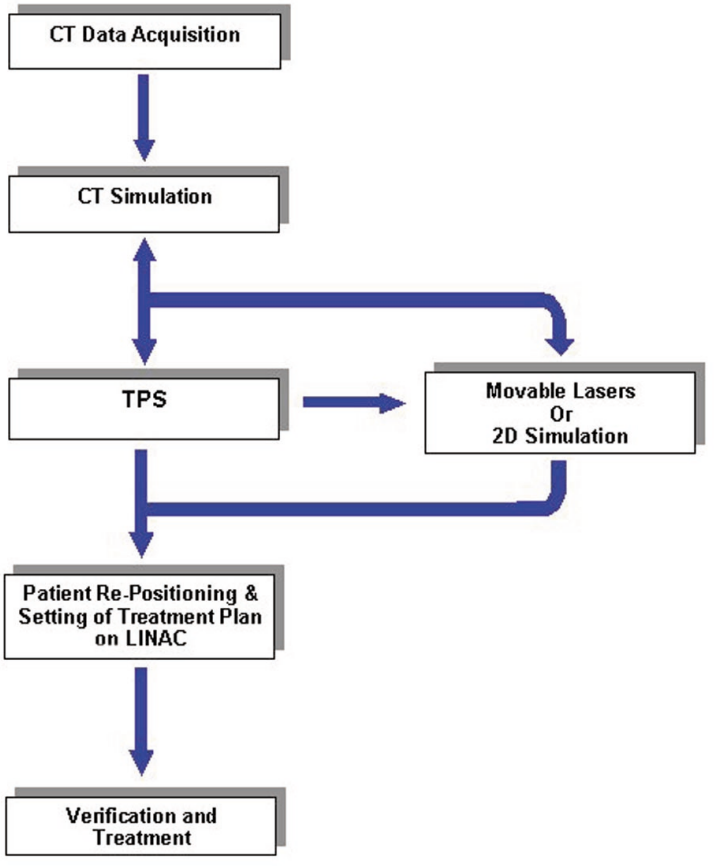

Figure 1. Typical clinical CT-Sim workflow pattern during the radiotherapy process

Communication requirements of a CT-Sim System

By assessing the above procedural steps, the importance of the communication requirements of a CT-Sim system can be evaluated. In developing EXOMIO the philosophy of the stand-alone CT-Sim system was adapted. In practice, the system is capable of interfacing to any CT scanner and to any radiotherapy treatment planning system *via* DICOM communication protocol.

The DICOM protocol is used for communicating digital images from the medical imaging devices, and the DICOM-RT supplements to communicate structures and beam data to & from the radiotherapy treatment planning systems and verification systems. All data sets can be stored in the EXOMIO server and can be accessed by & from any user installed on the local network of the institution.

Main system features of EXOMIO

The main system features can be separated into several categories and including visualisation features, volume definition tools, treatment field design, patient set-up and simulation plan documentation. In this paper only a small part of the visualisation capabilities are described: for further details see the publication by Karangelis et al [21].

EXOMIO layouts

EXOMIO has the ability to generate both 2D and 3D images using only the original CT data of the patient. The 2D images which can be displayed are the original axial CT, MR or PET images. Multi-planar reconstructions [MPR] can be generated in real time in the orthogonal, coronal and sagittal directions, and also in any oblique direction. The 3D reconstructed images are a vital part of CT-Sim systems in order to simulate the patient anatomy and the images generated from the real X-ray simulator or from the treatment machine.

The first EXOMIO 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 [RMV], together with the axial slices. The second layout is composed again of four windows: containing images in the three orthogonal slice planes and the OEV. This layout is ideal for navigation through the CT volume, for volume delineation and to observe complex radiation field arrangements.

The third and final EXOMIO layout contains all the images described above. This layout has six windows emphasising the size of the BEV image. This is because we found that physicians feel most 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 accommodate large amounts of data, from 40 to 300 image 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* a network directly to any CT scanner that supports the DICOM protocol. The system allows the adaptation to any linear accelerator configuration via 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 components and the description of the component's dimensions, for example, a multileaf collimator [MLC].

Volume visualisation

It can definitely be stated that 3D image reconstruction using volume rendering is the most essential component of a CT-Sim system. Thus CT-Sim might offer unique visualisation features that no conventional X-ray simulator system can provide. Because of the use of CT, the patient anatomy is obtained using adjustable field-of-views specifically selected for each patient study.

3D reconstruction of the complete patient anatomy for different anatomical sites is of great benefit for clinicians. It is emphasised that only a small part of the patient's anatomy can be visualised using a conventional X-ray simulator during the fluoroscopy mode. This is a significant disadvantage and is due to the limited size of the detection surface of the image intensifier. On the radiographic film this problem is improved but radiographic images suffer from other limitations.

The rendering pipeline used in EXOMIO is based on the work of Sakas [24]. In BEV we use perspective projection and in the OEV parallel projection but both views support the same illumination models. The transparent mode uses maximum intensity projection [MIP], see Sakas et al [25], and also X-ray [22] and surface reconstruction modes using iso-value, gradient [23] and semi-transparent methods.

In both illumination models [surface and transparent] selected tissue ranges using a linear or a triangular look-up table can be visualised. 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 is 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. These factors 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 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 in 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 the aim is to try to simulate the attenuation of the X-rays through the digital patient's body.

The manipulation of tissue properties such as the mass attenuation coefficient, assist the generation of unique images which simulate the physical principles of radiographic imaging. The most common example is the generation of megavoltage DRR images for direct comparison with portal images. DRR images also provide unique anatomical information for the clinician that no conventional X-ray device can produce. An example of different X-ray reconstruction modes is illustrated in Figure 2.

Another type of 3D image which is very important 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 image presentation concept is extremely suitable for assessing the configuration of the radiation beam in three dimensions.

EXOMIO supports the visualization of the irradiation beam, with shielding block arrangements, as 3D semi-transparent 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 3.

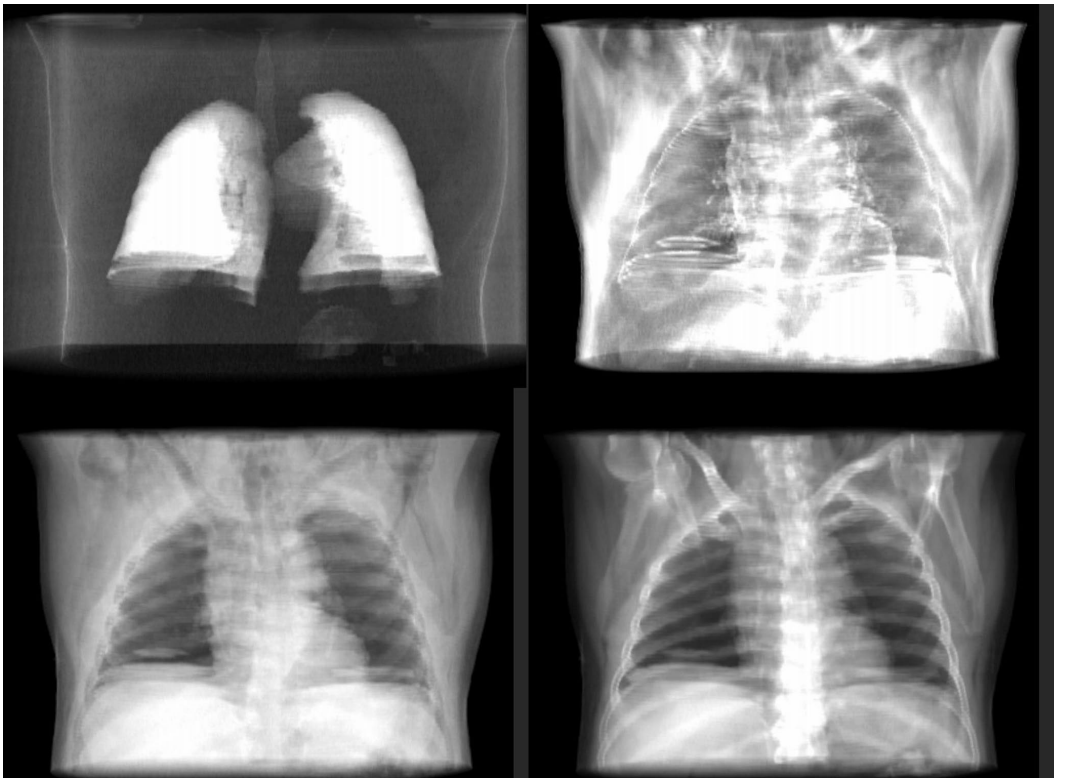

Figure 2. DRR modes from EXOMIO which have been generated using different tissue ranges: lung [*top left*], fat [*top right*], muscle [*bottom left*] and the full range of tissues [*bottom right*]

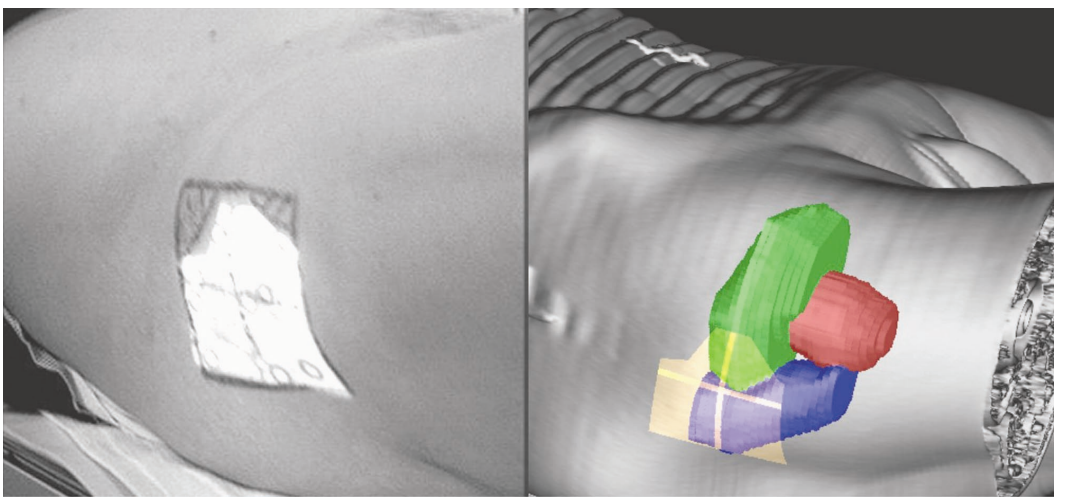

Figure 3. Visual comparison: real *versus* virtual. Light field projection on the actual patient's skin using a conventional X-ray simulator [*left*]. The simulated light field on the 3D reconstruction of the patient's skin surface [*right*]

Volume definition tools

Target volume and critical structure definition is a complex and time consuming process in radiotherapy: although the complexity varies for different anatomical sites. In CT-Sim and plan evaluation, 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 in EXOMIO. The system thus allows the user to draw contours around the tumour as target [PTV] and around normal tissues and organs of interest on a slice-by-slice basis. This 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 sagittal and coronal planes. 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 for copying to inferior and posterior slices.

Organs with large differences in their radiation dose distributions can be segmented semi-automatically. In terms of user effort the only action required from the user is the selection of a starting point for the algorithm on the original axial slices. The complete 3D geometry of the organ will be traced automatically.

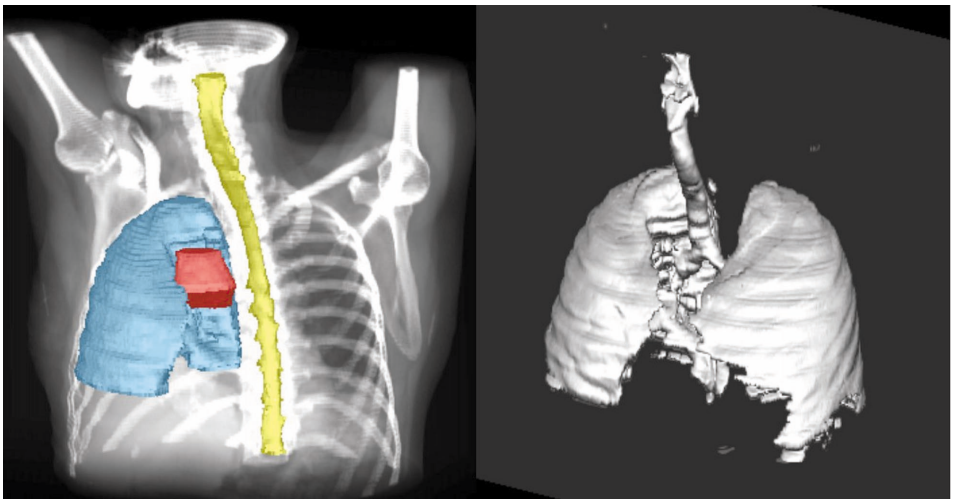

Figure 4. 3D reconstruction of segmented structures. The coloured structures have been segmented manually and semi-automatically [*left*]. The complete trachea and lung volume has been extracted automatically [*right*]

Some of the organs of interest which are highly radiosensitive and which are therefore of vital importance in terms of minimising the radiation dose, are the lungs, the spinal cord and the trachea. In addition to these organs, the external body contour can be extracted in a similar manner. The contours that are generated semi-automatically can be manipulated and modified in 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 4 illustrates two different 3D reconstruction examples of segmented structures.

Results: case history

Cancer of the Prostate

The patient is 75 years old with stage $T_3N_0M_0$ disease. The radiation fields cover the entire prostate gland and include safety margins. CT slice thickness was 3 mm with a 3 mm slice distance using spiral CT acquisition and a 512 x 512 pixel matrix. A total of 101 CT slices were required for this patient. Figures 5-8 relate to this patient.

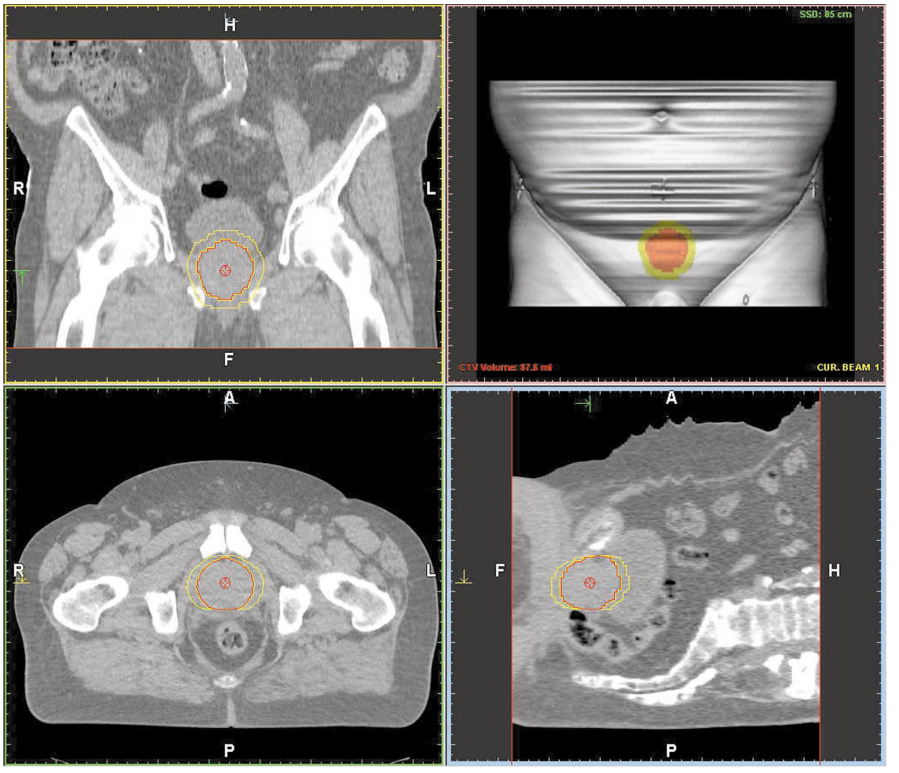

Figure 5. Automatic extraction of the PTV from the delineated CTV using EXOMIO by applying user defined clinical margins. The extracted PTV and CTV are shown in different colours in the three major planes and in the 3D OEV view. 3D anisotropic margins have been used in this case: 10 mm in the lateral and 10 mm in the cranio-caudal directions but 0 mm [that is, no margin] in the ventro-dorsal direction. EXOMIO permits the definition of an individual margin value in any direction, for example in left lateral and right lateral directions

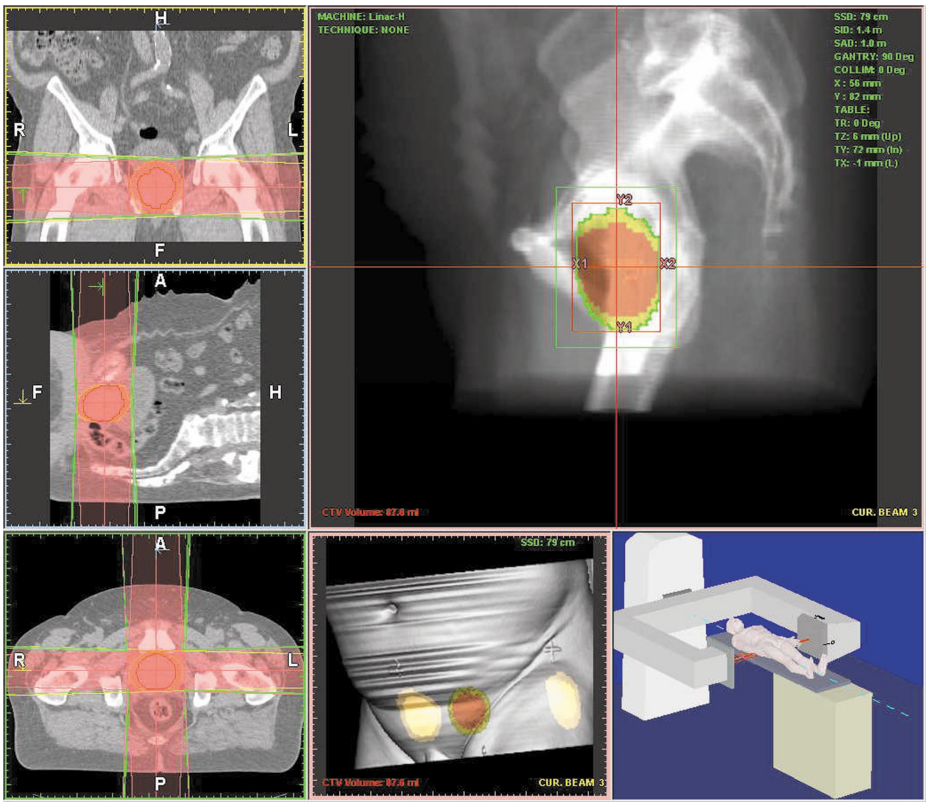

Figure 6. Planning procedure overview. Coronal plane view [*top left*], sagittal plane view [*centre left*] and CT slice with the four fields [*bottom left*]. DRR for the AP field [*top right*] and the OEV showing the patient, the projections of the light fields on the skin for all fields and the 3D PTV [*bottom centre*]. 3D view of the room with the virtual simulator and patient [*bottom right*]

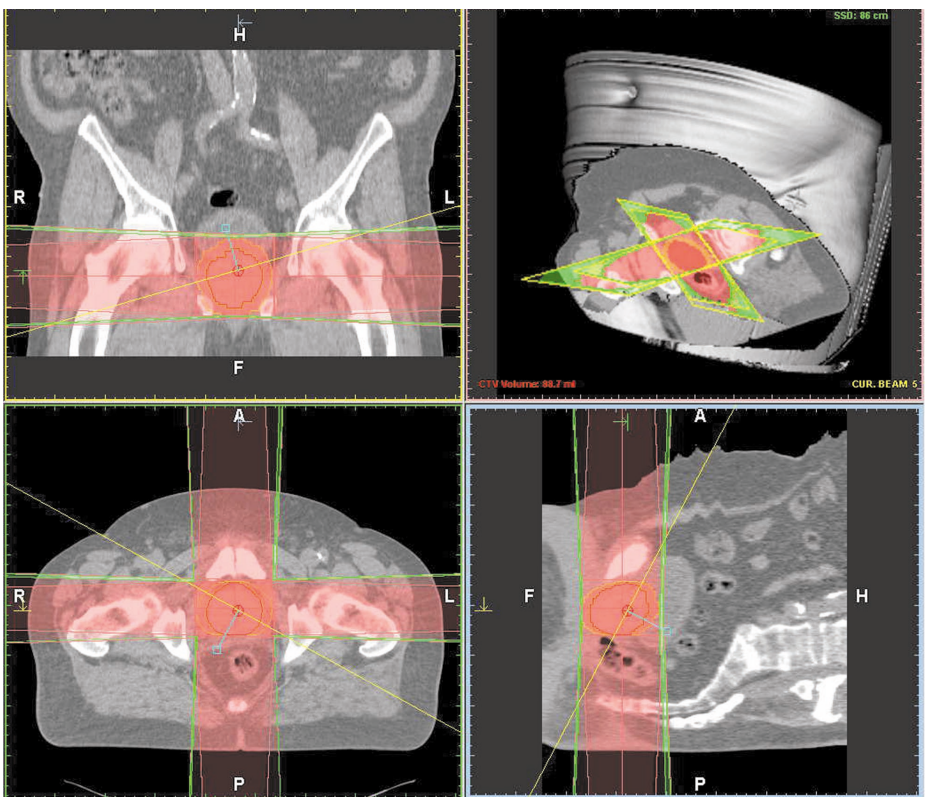

Figure 7. Evaluation of the four-field box technique making use of the oblique cut visualisation tools of EXOMIO. Coronal plane view [*top left*], sagittal plane view [*bottom right*], CT slice [*bottom left*] and OEV with oblique cut, field geometries and 3D PTV [*top right*]. The yellow line in the three major planes indicates the position of the oblique plane viewed in the 3D OEV window

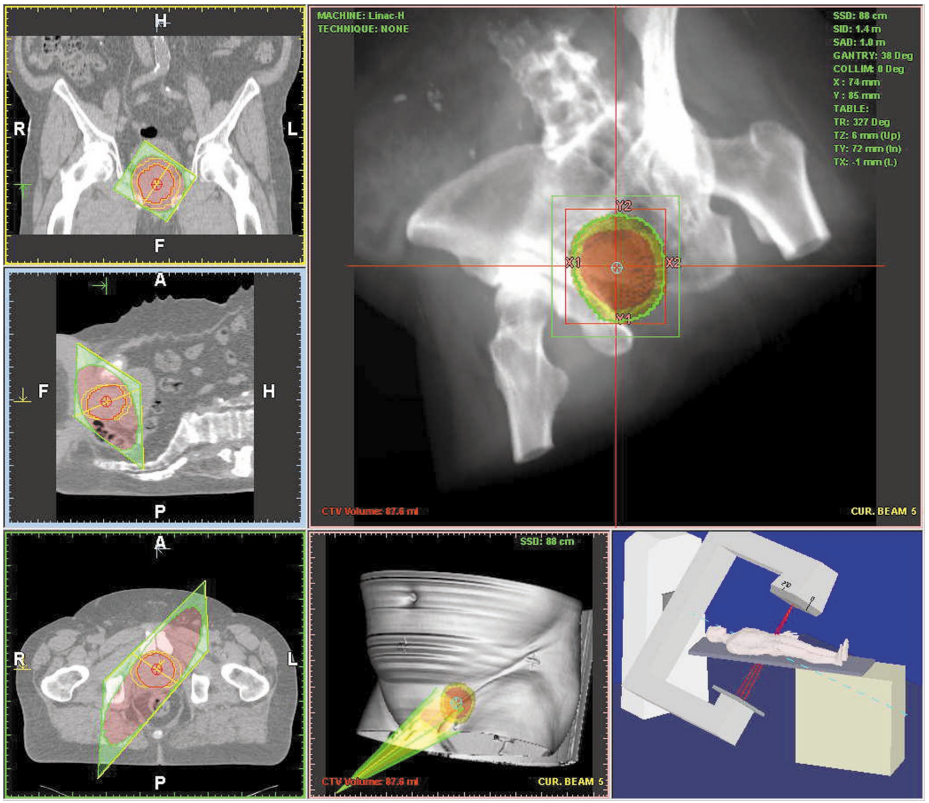

Figure 8. Planning an additional fifth beam which is non-coplanar to the four fields of the box-technique. Coronal plane view [*top left*], sagittal plane view [*centre left*] and CT slice showing the fifth field [*bottom left*]. DRR for the new fifth field with the automatically on-PTV adapted block: making this an irregular field [*top right*]. OEV showing the patient, the beam cone and the light field projection on the skin for the fifth field and the 3D PTV [*bottom centre*]. 3D view of the room with the virtual simulator and patient [*bottom right*]

Discussion

The advantages of CT based virtual simulation are well known and include the fact that target volumes and critical organs and structures can be effectively defined and displayed in multiple planes: axial, coronal, sagittal or oblique. Improved manual and automated contouring tools greatly simplify the task of normal critical structure, tumour, and target volume [PTV] delineation. A direct interface to the treatment planning system also permits efficient virtual verification.

In CT-Sim it is possible to display at any given time a large amount of information on the same screen. This can include where the DRR is displayed; the room view including a 3D model of the simulator or the treatment machine; and the OEV 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 it is possible to observe a greater percentage of the patient's volume than can be achieved with a conventional X-ray simulator: because fluoroscopy is limited by the dimensions of the image intensifier. This is emphasised by the fact that in the Klinikum Offenbach almost 1,700 patients underwent CT virtual simulation within the last year.

Clinically, the EXOMIO CT-Sim system can simulate all treatment cases and can therefore completely replace the conventional X-ray simulator. The modification required in the CT room was the installation of the laser marking system for the registration of the treatment reference point. This was similar to the installation in the linear accelerator room. In addition, a flat CT table top had to replace the original curved table top.

Visualisation of a multileaf collimator [MLC] field is only possible with CT-Sim and this is most important because of the widespread use of MLCs.

The validation of beam geometries in a conventional 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. With CT based simulation the following are used in addition: the entire patient anatomy, all tissues identifiable using CT. Also, most importantly, imaging is in 3D and not in 2D.

The most critical factor for the promotion of CT-Sim systems has been the rapid technological development of the CT scanners. Currently all CT manufacturers can provide spiral CT capabilities. Standard spiral CT devices, such as the, Siemens Somatom Emotion, allow the acquisition of a single slice with 0.8 to 1.0 second, thus the acquisition of 80-120 slices can occur in only a few minutes.

The main drawbacks of low acquisition rates for the radiotherapy, as well as for the diagnostic imaging, are breathing artifacts and internal organ movements. This is particularly true for the thoracic and abdominal regions, where they cause significant blurring artifacts in the reconstructed CT slices. The solution to this problem could be the fast, multi-slice CT scanners that allow four and more slice acquisition within 0.5 seconds: for example the Siemens Volume Zoom.

Multi-slice CT scanners acquire thin slices, thus giving higher resolution in the X, Y and Z axes. High resolution CT images make the target definition process easier, faster, and more effective due to the enhanced boundaries and accurate location of structures. Also, the reconstruction of the volumetric images can be improved, with BEV and OEV providing more precise 3D illustration of the internal structures assisting the accurate configuration of the radiation field: see Figure 15. Fast acquisition and manipulation of high resolution CT data therefore offer a great advantage for the development of future IMRT treatment strategies.

Conclusions

CT-Sim is a technological advance that has already been tested in our clinical environment with demonstrable advantages particularly for complicated field arrangements. The new, innovative EXOMIO virtual simulator system is a very useful additional tool for the radiation oncologist and makes the requirement for a conventional X-ray simulator redundant.

A significant advantage of the EXOMIO software is that it can run on portable computers such as laptops. This makes the CT-Sim concept extremely cost-effective. The system can be integrated immediately into the clinical environment via a direct interface to the CT scanner.

The advantages of CT-Sim are not limited only to those mentioned above. Combination of different diagnostic [for example MR and PET] and radiotherapy [for example MV portal detectors] imaging modalities will make the CT-Sim an even more effective tool in radiotherapy.

In the future, it is very probable that CT-Sim will become the *standard* in all radiation oncology departments.

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