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Telematics enabled virtual simulation system for radiation treatment planning

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Abstract

In this paper, GALENOS, a Telematics Enabled Virtual Simulation System for Radiation Treatment Planning (RTP) is described. The design architecture of GALENOS is in accordance with the dual aim of virtual simulation of RTP, i.e. to allow (a) delineation of target volume and critical organs, and (b) placement of irradiation fields. An important feature of GALENOS is the possibility for on-line tele-collaboration between health care professionals under a secure framework. The advantages of GALENOS include elimination of patient transfers between departments and health care institutions as well as availability of patient data at sites different than those of his/her physical presence.

Keywords: Radiation treatment planning; Virtual simulation; Collaborative work; Telemedicine

1. Introduction

Radiation therapy is defined as the use of high-energy ionizing radiation for therapeutic purposes [1,2]. Radiation therapy is recommended at some stage of most diagnosed cancer cases and is considered to be the most effective non-surgical treatment modality. Radiation therapy methods can be categorized into external beam radiotherapy, where radiation produced by a source external to the patient, usually a linear accelerator, is delivered to the treatment volume, and brachytherapy, where radiation

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is delivered at a short distance by radioactive sources placed at the vicinity of the treatment volume. The aim of radiation therapy is to destroy malignant tumors with minimal damage to normal tissues. In external beam radiation therapy, this may be implemented by selecting proper values for irradiation beam characteristics, including beam geometry, energy, total dose, dose rate and distribution [2]. In addition to this, partitioning the total radiation dose in consecutive sessions (fractionation) allows to control the biological effect at the normal and malignant tissues. The entire procedure is called Radiation Treatment Planning (RTP) and involves a series of interdependent steps, the execution of which can only be carried out efficiently by qualified personnel using dedicated hardware and specialized software.

In order to determine the position of the target volume and to display the treatment fields, conventional techniques of RTP make use of the treatment simulator. The treatment simulator is an apparatus that possesses identical geometrical, mechanical and optical properties compared to the radiation treatment unit, while employing a diagnostic X-ray tube. Alternatively, anatomical structures delineation and placement of the irradiation fields can be carried out using a Virtual Simulation (VS) system [3,4], a software system that makes use of a digital model of the patient created from tomographic (Computed Tomography—CT or Magnetic Resonance Imaging—MRI) data.

Moreover, putting into practice the continuous advances in telecommunications, which have vastly contributed to the establishment of tele-radiology [5–9] networks, real time information flow can extend beyond the physical boundaries of the Local Area Network (LAN) of a clinic allowing real-time collaboration between remote users. Thus, with the introduction of virtual simulation, a wide area of possible telematics applications in radiation therapy can be identified [10,11]. These include application scenarios for providing second opinion in the RTP procedure and for supporting continuous medical education in radiation oncology.

In this paper, a telematics enabled VS system, named “GALENOS”, is presented, aiming to replace in certain cases the use of the conventional simulator machine in the RTP process. In the following sections, the main features of GALENOS are described in detail. In Section 2 the RTP workflow is presented and the role of VS is highlighted. In Section 3 a general overview of the functionalities provided by the graphics-based GALENOS VS system is given, followed by a brief architecture description of the collaborative environment. Section 4 reports the results obtained from the pilot application of the GALENOS VS system. A discussion regarding the potential adaptation of the GALENOS VS system to the web environment, along with specific application scenarios and corresponding benefits are given in Section 5. Finally, concluding remarks are presented in Section 6.

2. Radiation treatment workflow and virtual simulation

The conventional radiation treatment process in external beam radiation therapy generally involves the following tasks (Fig. 1) [12]:

1. Disease diagnosis. This may be based on CT, MRI, or other diagnostic imaging modality and can be performed in any properly equipped hospital/diagnostic center.
2. Localization of tumor area. The main objective of this step is to determine the optimal treatment position for the patient. This is achieved using the “conventional” radiotherapy simulator, where the patient is appropriately aligned with respect to his anatomical landmarks (bony structures) with the

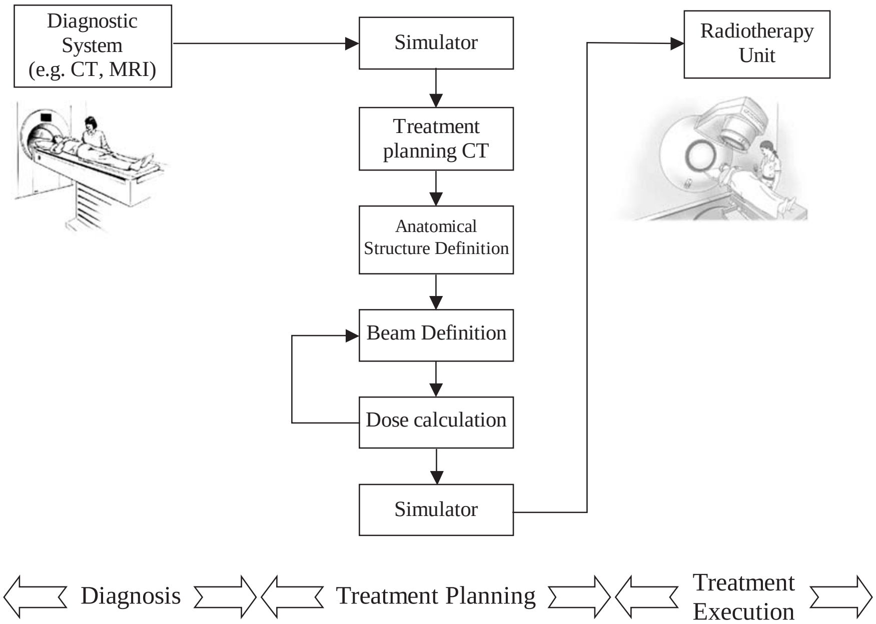

Fig. 1. Workflow in conventional radiation treatment process.

guidance of the provided fluoroscopic imaging. In some cases, proper positioning requires the use of specialized immobilization devices.

3. Tomographic imaging for treatment planning. The goal of this step is to acquire the necessary three-dimensional (3D) anatomical data of the patient that will be used in the planning process. To this end, a treatment planning CT scan is obtained with the patient setup at the treatment position, including any immobilization devices, as determined in the previous step. Since the quality of treatment plan depends on the detail of anatomical data, a slice spacing of no more than 4 mm is used for the tumor area, whereas for neighboring regions the slice spacing should not exceed 8 mm. In some cases, complementary imaging modalities (MRI, Positron Emission Tomography—PET) may be used to assist tissue definition. External markers, made of radiologically opaque material, are placed on the patient's body before data acquisition in order to establish a point of reference in the CT data set.
4. Tumor and critical structure definition. The goal of this step is to define the area to be irradiated and the structures to be protected. This is achieved using a dedicated software system.
5. Beam definition and field shaping. At this step the geometrical characteristics (direction, isocenter, field shape) of the irradiation beam are defined with the dual aim to fully encompass the tumor volume while avoiding the critical structures. To this end, Digital Reconstructed Radiographs (DRRs) and 3D visualization tools are usually employed provided by a dedicated software system.
6. Plan evaluation and optimization. The goal of this step is to evaluate the anticipated dose distribution for the defined plan. It involves the dose calculation at the tumor area and the critical structures. The result is evaluated using dose volume-histograms, isodose curves or isodose surfaces. Usually this step dictates the need for new beam definition resulting into an iterative execution of Steps 5 and 6 until the desired dose distribution is achieved, though this user-driven optimization procedure.

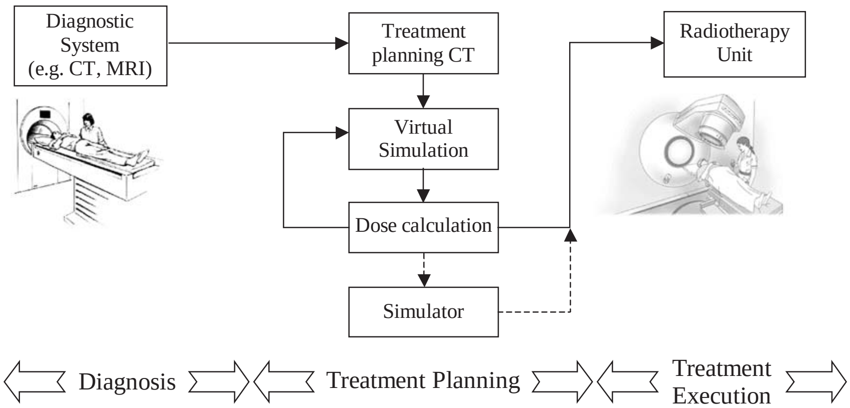

Fig. 2. Workflow in radiation treatment using a VS system.

7. Plan verification. This is performed by placing the patient in the "conventional" simulator at the treatment position and verifying the characteristics of the beams planned in Step 6.
8. Treatment execution. It involves the irradiation of the patient in the radiotherapy unit according to the pre-defined plan. Usually a verification system (electronic portal imaging) is used to assess the correct positioning of the patient.

With the introduction of the Virtual Simulation system, healthcare professionals can simulate the treatment process using a digital patient model instead of the real patient. In addition, the VS system provides the necessary tools to perform delineation of anatomical structures on the tomographic images, and virtual placement of multiple irradiation fields. In this way, the VS system can substitute the "conventional" simulator machine through the treatment process workflow. With the adoption of the VS system, Step 2 is usually eliminated, while Steps 4 and 5 are performed on the VS system. Subsequently, the results of the design on the VS system can be passed to dose calculation routines, and to dose distributions' evaluation and optimization modules (Fig. 2). Under this application scenario, the use of treatment simulator machine is limited to the verification procedure (Step 7) of certain complex cases, where an increased level of confidence is required.

According to the conventional workflow, the patient must move between hospital departments or even between hospitals. However, with the incorporation of the VS system in the treatment process workflow the need for patient's physical presence is reduced, resulting into:

- decreased waiting time for the patient,
- increased number of patients that may be treated,
- balanced and more productive workload for the medical personnel, and
- increased plan accuracy due to the reduction of error propagation during the process caused by successive repositioning of the patient in diagnostic and therapeutic systems.

3. General architecture description

The architecture of GALENOS VS system is modular as depicted in Fig. 3. According to the dual aim of the VS (i.e. delineation of anatomical structures and definition of irradiation beams), it incorporates

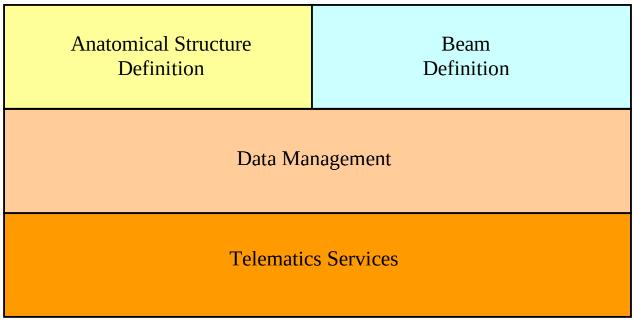

Fig. 3. Architecture of the GALENOS VS system.

two main user modules: one for anatomical structure definition and one for beam definition. The software system is complemented by the necessary data management modules and the telematics services.

GALENOS VS system offers a user-friendly interface, which includes 2D and 3D imaging functionalities, control fields, and custom-built tools aiming to facilitate the treatment planning process. The system can operate either in stand-alone mode or in tele-collaborative mode. The main features of GALENOS VS system are described in more detail below.

3.1. Data management—GALENOS database

The data managed by GALENOS VS system include imported data, system-generated data and system configuration data. Imported data are patient tomographic images (CT/MRI), system-generated data include anatomical structure definition data and beam definition data, whereas system configuration data include information related to available linear accelerators, data related to the users of the system and data needed for the tele-collaboration services (remote hospital IDs, IP addresses, etc.). Database access is carried out using standard Structured Query Language (SQL). GALENOS VS system follows the client-server model according to which, the database is hosted in a single fileserver allowing a number of independent GALENOS clients to operate simultaneously in the LAN of the radiotherapy department (Fig. 4).

The hierarchy of information entities managed by GALENOS VS system is presented in Fig. 5. The "patient" information entity lies at the root of the hierarchy tree and is followed by the tomographic data, the anatomical definition data and the beam definition data. The tomographic data consist of a set of tomographic images, the anatomical definition data contain a complete set of anatomical structure definitions and the beam definition data contain the characteristics of one or more irradiation beams. The relationship of entities along the direction root-to-leafs is one-to-many. The patient database may be queried according to patient demographic data (name/surname, sex, age, etc.), anatomical area of disease, and characteristics of the treatment plan including number of beams.

Data management allows: (a) Import of patient tomographic data directly from any digital imaging modality (CT or MRI) connected on the LAN using a custom built DICOM (Digital Imaging and Communications in Medicine, [13]) Server service. Alternatively, tomographic images in DICOM format can be imported manually, as individual files. (b) Storage/retrieval of produced radiation therapy plans (anatomical structures and external beams definitions). (c) Data export through either conversion of radi-

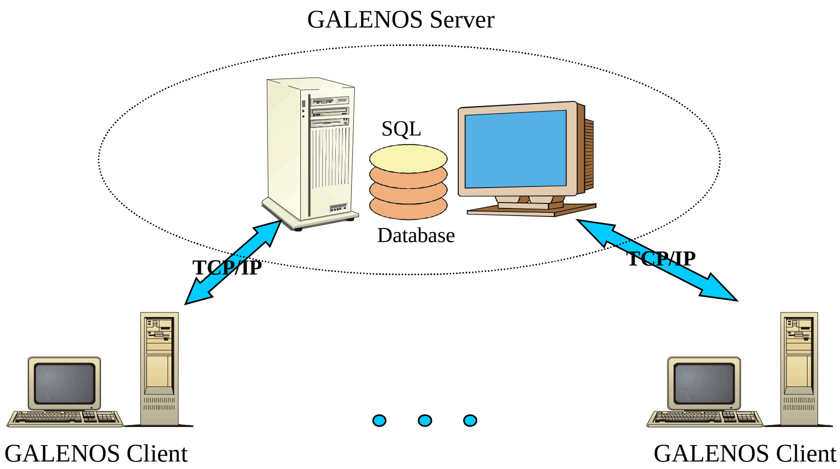

Fig. 4. Communication of the SQL database operating on a fileserver with any workstation of the LAN (GALENOS clients).

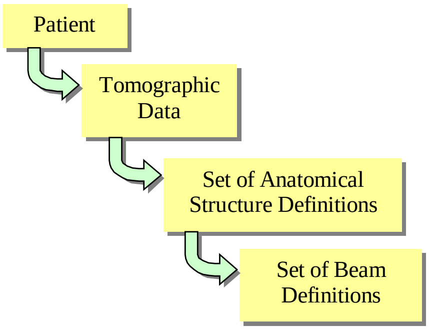

Fig. 5. The hierarchy of entities managed by GALENOS.

ation therapy plans in DICOM RT format [14] or print-out of characteristic parameters of RT plans, i.e. geometrical parameters of beams and Digital Reconstructed Radiographs (DRRs). The use of DICOM-based interfaces greatly facilitates the connectivity of GALENOS VS system with other devices in a radiotherapy department, without any need for specialized configurations.

3.2. Anatomical structure definition

In this module the user can define volumes of interest (VOIs) and localize external markers. VOIs are anatomical areas in the patient's body, which are significant for the RTP process. These, include the tumor area [15], neighboring critical structures and external body contour. The reference point for the digital patient model is provided by the external markers. The user-interface consists of two main imaging windows (2D and 3D) as shown in Fig. 6.

In the 2D imaging window the user can display the axial tomographic images of the patient and define the VOIs. Each contour consists of a number of ordered points defined on the axial image plane, whereas

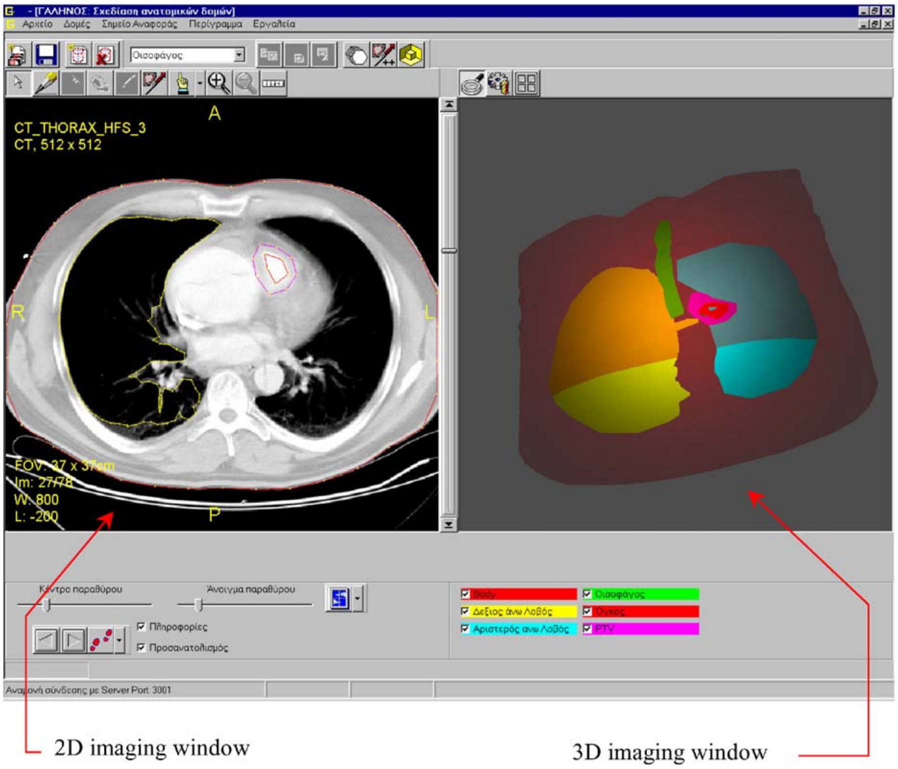

Fig. 6. GALENOS VS user interface for the definition of anatomical structures.

the 3D VOIs are made of consecutive 2D contours defined on different tomographic images. The software system offers automatic, semi-automatic and manual tools to facilitate anatomical structures delineation. Initially, the external contour of the patient is calculated automatically without user intervention. To this end, the body of the patient is separated from the table using an initial estimation of patient's positioning by calculating its geometrical center of mass and then using this point as initial seed in a seeded region growing algorithm [16]. Then, the user can define manually the contours of VOIs by selecting individual points defining the structure boundaries. In addition, GALENOS VS system offers a semi-automatic tool for the definition of contours in a group of successive tomographic images based on the previously described seeded region growing methodology for the separation of anatomical structures. In both cases, the final contour is obtained using a contour tracing algorithm [17] and subsequently rejecting a percentage of points according to the minimum distance between successive points and a curvature criterion [18]. Finally, a tool providing automatic expansion of VOIs in three dimensions allows the user to quickly create the Planning Target Volume (PTV) from the Gross Tumor Volume (GTV). A distance map [19] is obtained for each structure to be expanded and the structure is then recalculated by thresholding the distance map in the desired expansion distance.

In the 3D imaging window, the virtual model of the patient is presented on the basis of the user-defined VOIs, using surface rendering techniques. The external surface of each anatomical structure is first reconstructed by calculating the optimal triangulation between each pair of successive contours [20].

Then, the reconstructed surface is visualized as a set of triangular primitives using the OpenGL graphics library [21]. The user can rotate and move in real time the 3D model of the patient anatomical structures and zoom in and out of the 3D scene.

3.3. Beam definition

In the beam definition module, the user determines the geometrical characteristics of the irradiation beams according to the defined anatomical structures. The beam definition procedure consists of the placement of beams with respect to a patient-based reference point, as well as the setup of beams' direction and fields' size and shape. During the interactive procedure of beam definition, all treatment machine motions, including gantry, collimator and table rotations, as well as table translations, are simulated, taking into consideration the specific mechanical and geometrical properties of the available treatment units, which are stored in the GALENOS database. Although the default settings for the movements and scales of treatment units simulated by the GALENOS VS system are in accordance with the IEC standard [22], user defined settings are also supported.

The definition of irradiation beams is facilitated by tools for the automatic placement of treatment unit isocenter [1] to the center of VOIs (geometrical or center of mass) or to patient skin and tools for the automatic adaptation of field boundaries to accurately encompass any given VOI. The user-interface includes four visualization windows (Fig. 7) displaying:

1. a virtual view of the RT simulator (room view),
2. the beam's eye view (BEV),
3. 2D images in axial and non-axial planes, and
4. 3D views using volume or surface rendering techniques.

3.3.1. Room view

A virtual 3D view of the RT simulator with the patient in treatment position is presented. The room view augments health care professional's comprehension regarding machine settings. All simulator motions according to the IEC standard are simulated: translation of the table along the three Cartesian axes, rotation of the table and rotation of the gantry. The room view is automatically updated every time the geometrical characteristics of the beam are changed in the BEV window. The viewing direction and the 3D scene magnification (zoom-in and zoom-out) can be interactively defined by the user.

3.3.2. Beam's eye view

The BEV is a key component in the beam-definition module, since it resembles the fluoroscopic images acquired with the use of the conventional simulator machine. The BEV displays the trace of the irradiation field boundaries, the perspective projections of the VOIs and the DRR at the isocentric plane. The extraction of DRR is performed using ray casting [23], while a preview of DRR is available for real-time visualization, using Fourier volume rendering [24–27]. All geometrical characteristics of the beam are defined through the BEV window, specifically

- the beam isocenter by changing the table's position,
- the beam direction by rotating the gantry and the table, and
- the field shape by opening and closing the collimator jaws.

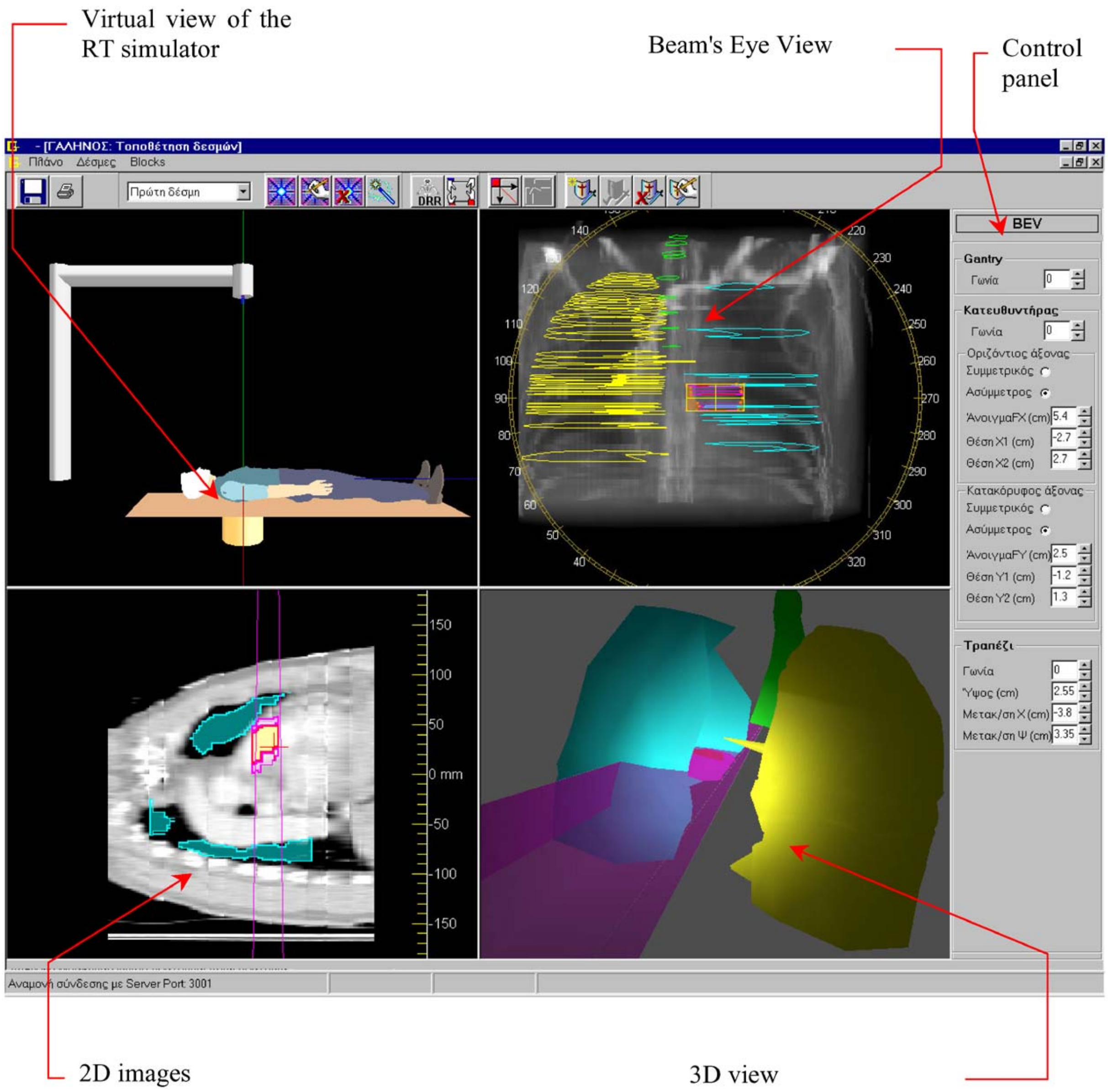

Fig. 7. GALENOS VS system user interface for the definition of beams.

Moreover, the user can draw blocks on the BEV window aided by a set of custom-built block editing tools.

3.3.3. 2D visualization

Patient's tomographic data (CT and MR) can be visualized in different planes (axial, sagittal, coronal and oblique). The original CT images are used for visualization along axial planes, while standard data interpolation methods are employed for the visualization of tomographic data along non-axial planes. The areas corresponding to already user-defined VOIs are appropriately colored by blending the gray scale tomographic image with the corresponding user defined color of the VOI. Moreover, the traces of the beam boundaries along the displayed plane are superimposed on the tomographic images providing a detailed presentation of the irradiated areas.

3.3.4. 3D visualization

The provided 3D views contain the results of either volume or surface rendering techniques serving as a tool for the evaluation of beam placement with respect to tumor and critical structures. Volume rendering visualization is obtained using the shear-warp factorization method [28] and the software system enables the user to interactively set the viewing direction and opacity values (mean and standard deviation) that correspond to specific Hounsfield units. The implementation of surface rendering visualization is based on the methodology that is used in the 3D imaging window of the anatomical structure definition module. In the beam definition module the user defined VOIs along with the surface boundaries of the irradiation beams are simultaneously displayed. The tools offered to the user include display or secretion of an anatomical structure or a beam, real time translation and rotation of the 3D objects, zoom-in or zoom-out of the scene.

3.4. Collaborative environment

The collaborative environment of the GALENOS VS system extends the capabilities of the stand-alone VS system, giving local and remote health care professionals the opportunity to co-operate for the delineation of VOIs and the placement of irradiation fields [29,30]. The implementation is based on a point-to-point communication scheme following the “What You See Is What I See” (WYSIWIS) paradigm [31,32].

To support the collaborative environment, both asynchronous (off-line transfer of data sets) and synchronous (on-line collaboration) data exchange schemes are employed. The indispensable condition for the realization of a collaboration session is that both collaborating parties possess the same data set, on which the treatment plan will be performed. Due to the rather large size of the communicated data (5–25 MB after lossless compression, depending on the number of tomographic images), the transfer of data sets is performed off-line. The term off-line indicates the absence of user’s interaction with the GALENOS VS system. To this end, the user can schedule data exchange jobs, which are stored in GALENOS VS system database and are handled by a custom-built data exchange service.

The main concept of the collaborating environment relies on the synchronization of the two GALENOS VS application (local and remote), in order to provide the collaborating parties with the same view of the application. A master/slave control relationship is employed, where the party having the role of the master is able to perform all actions of the VS, while the “slave” participant can only view the results of the master’s actions. The common synchronized operation of the two GALENOS VS applications is achieved by transferring the codified commands corresponding to user interface actions, from the master side to the slave side. Since only the command codes, along with the necessary parameters, are being transferred through the communication link, the latency in command execution between the two sides is minimal.

Special attention is given to security issues, which are raised by the introduction of tele-cooperative functionalities. More specifically, the information manipulated by the GALENOS VS system contains data related directly to identifiable persons, their illnesses and their treatment. Therefore, the introduction of electronic processing and transferring of such information, through the tele-cooperative work should be directly followed by the implementation of a security framework, which eliminates any possible violations of the authenticity, integrity, confidentiality and availability of data [33–36]. The fulfillment of the security requirements is realized with the employment of authentication procedures and access control methods on the LAN, and encryption techniques, digital signatures and certificates on the connection between remote radiotherapy departments. User access to the GALENOS VS system is controlled by a password and/or a biometrics-based procedure (fingerprint scanning).

3.5. Hardware and software requirements

GALENOS VS system runs on PC-based platforms operating under Microsoft Windows NT™ (version 4.0 or higher) operating system. While the minimum required processor speed is 600 MHz, GALENOS VS system is capable of exploiting the presence of multiple CPUs on the same motherboard, thus resulting into an increased performance of the VS system. In particular, an almost linear increase of performance has been recorded for DRR calculations [27]. The minimum RAM requirement is 256 MB (512 MB recommended) and the hard disk requirement is less than 10 MB, excluding the patient database. Moreover, GALENOS VS system requires OpenGL compatible graphics display adapter with a minimum of 32 MB of memory. The client–server version of the software system requires Microsoft SQL Sever™ (version 2000) while the stand-alone version can operate using Microsoft Access™.

4. Results

In order to evaluate the technical and functional characteristics of the GALENOS VS system, a preliminary technical pilot study has been conducted involving four radiotherapy departments located in two different cities. A point-to-point communication scheme between the radiotherapy departments was realized using Basic Rate Access ISDN lines. Similar hardware platforms were used for all participating sites consisting of dual Pentium™ II 600 MHz workstations with 256 MB of RAM. According to the evaluation scenario, a number of clinical cases were selected and the corresponding data sets were transferred between the collaborating sites using the provided data exchange time-scheduling facility (Fig. 8). The initialization of a secure communication channel was about 2.4 s, while the average throughput of the link (including encryption/decryption operations) was 60.583 kbps per ISDN data channel.

After successful completion of the off-line data set exchange, the users can collaborate on the design of a treatment plan whereas any party possessing the common data set can initiate the collaborating session by selecting the appropriate partner (Fig. 9). Collaboration on the GALENOS VS system can be performed either on anatomical structure definition, or beam definition. During the pilot study a number of collaborating sessions has taken place and the mean latencies of the command execution between the collaborating parties has been recorded. A UDP connection has been used for the exchange of commands related to mouse movements, while a TCP/IP connection has been employed for all other events. The mean latency detected for the former was 0.06 s, while the mean latency of the later was 0.27 s.

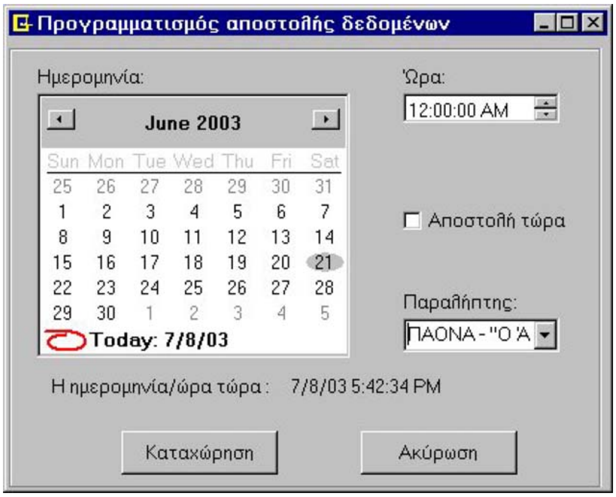

Fig. 8. GALENOS VS system user interface for scheduling data exchange jobs.

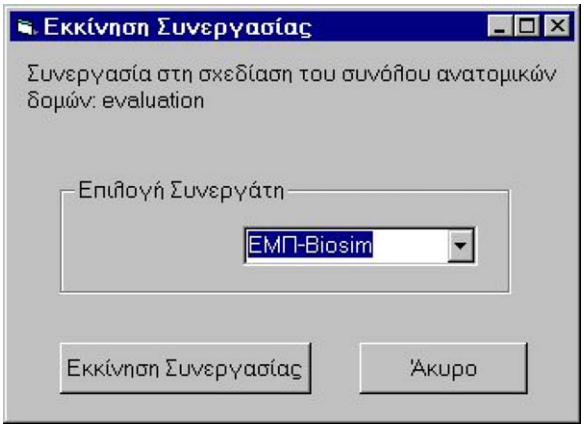

Fig. 9. GALENOS VS system user interface for initiating the collaborating session.

A comprehensive pilot study aiming to evaluate the operational effectiveness of GALENOS VS system from the user's perspective is currently underway and the full results will be published separately.

5. Discussion

Each patient entering the radiotherapy process requires careful treatment planning, including clinical evaluation, therapeutic plan, virtual simulation and isodose planning. The amount of data produced during these phases is relatively large and is usually located at distinct sites. Taking into consideration that patients undergoing radiotherapy are obligated to take additional examinations, monitoring the state of the disease before and after the treatment, the management of patient data related to radiotherapy, turns out to be a challenging task, especially within the context of increased patient mobility. Moreover, the adoption of 3D conformal radiotherapy concept, the introduction of new treatment techniques (intensity modulated radiotherapy, etc.) and the availability of state of the art equipment (multi-leaf collimators, electronic portal imaging, etc.) in clinical practice, raise the complexity of the problem of defining an optimal treatment plan. The introduction of telematics techniques in the field of RTP can significantly contribute to the quality of the provided radiotherapy services. GALENOS VS system represents one of the first steps towards the introduction of telemedicine into clinical radio-oncology, while the transfer of the collaborative environment to the web [37] offers new challenges and provides the framework for the development of novel applications.

The adoption of web technologies, already in use by other telemedicine applications [8,9,38], can offer a significant number of advantages, since health care professionals will be able to collaborate on VS, regardless of their location, the platform and the RTP system they are using. According to the proposed architecture the VS system can be transformed into a client–server application on the web accessed through a simple web-browser. Under this implementation framework, different application scenarios can be identified including centers of excellence and support, tele-consultation and continuous medical education.

The "Centers of excellence and support" scenario aims to support the operation of small satellite radiotherapy units in underserved areas. It is well known that small regional radiotherapy clinics do not usually have the technological resources or the required expertise due to budget restrictions or unwillingness of highly qualified personnel to work in rural areas. Thus, to maintain a high-quality level of radiotherapy services, and accessibility outside larger centers, satellite clinics can be connected with metropolitan hospitals [11], where centers of excellence and support perform the entire treatment planning procedure using a web-based VS system. Under this application scenario, dose calculation modules should be incorporated into the web-based VS system and dosimetric data of the satellite clinic treatment machines should be available to the metropolitan clinic.

The tele-consultation scenario addresses the need of individual health care professionals working in the radiotherapy field to collaborate regardless temporal, spatial or application specific restrictions. The processes of optimal tumor delineation and beam placement rely heavily on the experience of the radiation oncologist or the medical physicist. Therefore, health care professionals often need a second opinion on the plan they are designing. To this end, a web-based VS system can be employed providing tele-collaboration functionalities on demand between remote health care professionals.

Moreover, the collaboration procedure on the design of a treatment plan resembles the educational process, where the tutor of an educational session interactively introduces methods for designing a given treatment plan, and the trainee is able to perform a design upon tutor's request. Thus, according to the continuous medical education scenario, a web-based VS system can provide the technological framework supporting medical training programs and continuous education of health care professionals, giving the opportunity to participants to actively interact in real time and share the experience acquired in different radiotherapy departments.

The above-described scenarios represent only a sample of potential new applications arising from the adaptation of the traditional stand-alone VS software system to the web environment. For example, a web-based VS system can serve as a tool for quality assurance in radiotherapy practices [39]. In fact the benefits from such a development can be significant for both manufacturers and users of VS systems. However, issues related to the security of the transferred data, as well as the technological infrastructure permitting the broadband access of health care institutions to the Internet need to be carefully addressed.

6. Conclusions

Virtual simulation is an important tool in modern radiotherapy clinical practice. It allows radiotherapists to use efficiently a large amount of CT data and it advances the use of a “virtual patient” model in the RTP procedure. Close collaboration between virtual simulation and treatment planning systems is required in order to avoid unnecessary repetition of tasks and to ensure correct use of CT data.

The VS system GALENOS offers tools to define anatomical structures and place external beams which, in conjunction with advanced 2D and 3D imaging functionalities, improve the RTP procedure. In addition, the telematics capabilities of the GALENOS VS allow transmission of tomographic data, thus reducing patient transfers and improving workflow in the radiotherapy department. On completion of tomographic data transmission, remote system users are able to collaborate with local users for the design of a treatment plan. Consequently, the level of services can be improved especially in the case of small radiotherapy clinics that do not possess the experience nor the equipment (treatment planning software) of large radio-oncology centers.

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