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Simulated Surgery on Computed Tomography and Magnetic Resonance Images: An Aid for Intraoperative Radiotherapy

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ABSTRACT Intraoperative radiotherapy (IORT) is a relatively new technique in which irradiation with electrons is performed during an open surgery procedure. This approach poses significant problems in obtaining accurate dosimetry, since neither the pre- nor the postoperative patient images actually matches the irradiation field. Our objective was to implement a software tool able to provide an estimate of the dose distribution, overcoming the problem of the geometrical mismatch between the images and the surgical field during the irradiation.

The program was developed in the C programming language, on a noncommercial version of a Philips EasyVision workstation. The application allows to create a new data set by manipulating the preoperative computed tomography and magnetic resonance images in order to simulate the final geometry of the surgical area during the IORT procedure. The exact dose distribution can then be calculated by transferring these new images to a standard radiotherapy planning system. Also an approximate dose distribution can be quickly displayed by superimposing isodose curves obtained from a water phantom. The proposed approach introduces a helpful tool for dosimetry and planning in IORT protocols, improving their accuracy and safety and allowing for more objective quality control and patient follow-up. Comp Aid Surg 2:333–339 (1997).

Key words: **dosimetry, intraoperative radiotherapy, surgery simulation, image processing**

INTRODUCTION

Intraoperative radiotherapy (IORT) is a therapeutic technique combining surgery and radiotherapy: A high single dose of fast electrons is delivered in a surgically defined area, while trying to protect normal tissues from the radiation beam, either by retracting the mobile structures or by shielding the fixed ones.[1,3–5,11] Before radiation delivery to the patient, it is necessary to define the organs and structures adjacent to the tumor that have to be protected. To achieve this, the beam is shaped for optimal performance with specific collimating devices, known as applicators.[9] Applicators are characterized by two geometrical parameters: diameter and bevel. Common values

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used at our institution are 5, 6, 7, 9, and 10 cm diameter, with bevel angles of 0°, 15°, 30°, and 45°. The applicator diameter must be the minimal diameter that still guarantees complete irradiation of the target zone. Because the target zone is not always easily accessible from outside the patient,[2] an appropriate selection of the bevel makes the applicator positioning easier, insofar as it may be introduced into the surgical volume from different directions.

Planning and dose distribution calculation are necessary in almost all modern radiotherapy procedures. They are usually performed on the basis of tomographic studies, i.e., computed tomography (CT) or, sometimes, CT/magnetic resonance imaging (MRI).

In the case of IORT, there is a noticeable obstacle; the surgical procedures preceding the irradiation introduce significant changes in the patient geometry. Therefore, any pre- or postoperative CT or MRI measurements no longer correspond to the actual geometry during irradiation, making it impossible to perform IORT planning or dose evaluation with those images.[7]

The main causes of this mismatch are a) the surgical manipulations themselves (tumor excision and retraction of mobile structures from the beam trajectory) and b) the insertion of the collimating device (applicator). For these reasons, actual dose distribution is very difficult to estimate. It is frequent in practice that IORT planning uses nothing better than rough approximations. Thus, any procedure able to improve the quality of the dosimetry could be extremely helpful for the radiation oncologist.[10] In this paper we propose an approach based on an interactive computer-assisted modification of preoperative CT or MRI in order to make them match the situation when the radiation is applied (surgery simulation), including the introduction and positioning of the applicator.

MATERIAL AND METHODS

The program has been developed on an EasyVision Open platform, a noncommercial version of the Philips EasyVision CT/MRI workstation.[6] This workstation includes facilities for the addition of user-developed routines (in the C programming language) as well as the use of a commercial image-processing package, SCIL-Image.[12,13]

The application works with preoperative CT or MR images of the patient. In our institution, CT data may come either from a Philips LX or a Siemens SOMATOM CT scanner. MR data are generated with a Philips ACS 1.5T machine. The linear accelerator is a Philips SL-18, and the radiotherapy planning system is a Focus SLP-9200. Data communication between the machines involved is established via network (Ethernet), optical disk, and DAT tape. Image formats are ACR-NEMA v2 and MERGE.

Clinical requirements for the system stated that the program should be fully interactive, should be icon and mouse driven, and should allow for a complete three-dimensional (3D) handling of the patient images and collimator positioning. With this goal, a dedicated user interface has been created for the application, which is shown in Figure 1. The 3D data presentation is performed mainly by means of three orthogonal views, although a 3D surface rendering can also be generated on demand.

To simulate the surgical excision of anatomical structures, the image data are edited by segmenting them, either manually or assisted by thresholding and contour detection algorithms. Simulation of the applicator insertion is implemented by making use of a previously stored set of images corresponding to each of the actual bevels commonly used in IORT procedures. The program retrieves these images from disk, changes their size according to the selected diameter, and displays them on the patient CT/MRI as a color overlay. In this way, the user can quickly try different models, choosing the one that best fits the geometrical characteristics of the surgical field, in order to optimize the isodose distribution.

The visualization of the approximate dose distributions is based on a set of isodose curves obtained with a water phantom, as part of the standard periodic calibration of the accelerator. A specific data set is available for each combination of applicator model and beam energy. Accuracy of this dose distribution is limited by the fact that the water phantom isodose curves correspond to a homogeneous media and do not take into account some important factors, such as the existence of tissues of different density or air–liquid interfaces or the morphology of these interfaces.

By following the same procedure described above for applicators, the whole set of water phantom isodose curves was converted into 3D images and stored on disk. These curves are retrieved whenever the user wants to calculate an approximate dosimetry. They are then superimposed on the patient images as color overlays. The display of these curves makes use of a color

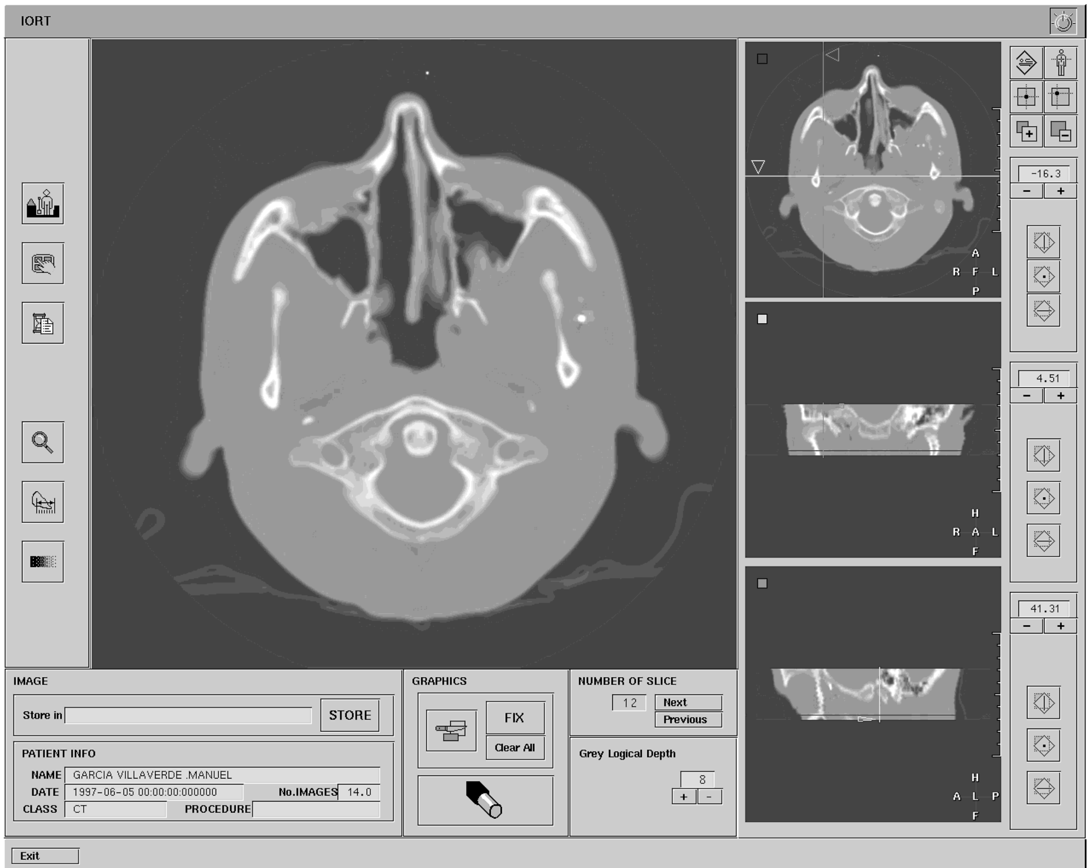

Fig. 1. General layout of the user interface (running in Edit mode).

table for better visualization of the different isodose levels. It produces an immediate visual effect of the 3D dose distribution of the radiation delivered.

RESULTS

At the beginning of a simulation session with this application, the user selects from the patient database the CT or MRI study with the preoperative set of images to be processed. The whole data set is displayed in three small orthogonal views, initially representing the axial, sagittal, and coronal planes (Fig. 1). The user can easily set any other orientation (for instance, the beam's-eye view is sometimes useful). This 3D viewing mode is quite simple and easy to learn, offering the user a powerful mouse-driven instrument to simulate intraoperative navigation. The program has three working modes (Table 1).

The first mode (''Edition'') corresponds to the first step of an IORT protocol, the surgical intervention for tumor resection (Figs. 2, 3). This working mode allows the radiation oncologists to modify the preoperative CT or MR images interactively in order to make them match the final aspect and geometry of the area. The different 2D slices of the patient are displayed on the larger viewport, where they are manually or semi-automatically edited,[8,14] thus simulating the surgical removal of anatomic structures (Figs. 2, 3). This manipulation must be performed on all the different slices.

The second mode (''Insertion'') corresponds to the applicator insertion and positioning in the real IORT protocol (Figs. 4, 5).
This working mode provides tools for applicator repositioning in 3D, until an adequate fit is

Table 1. Working Modes

Real surgical intervention	Surgical simulation	Application working mode
Tumour resection	Structure resection (cutting tool)	Edition mode
IORT protocol	Collimator cone insertion	Insertion mode
	Dose estimation	Dose mode

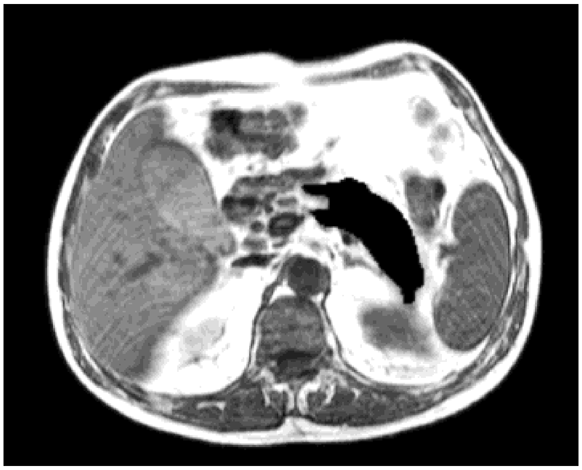

Fig. 2. MR slice being processed to simulate an organ extraction.

achieved. The applicator must be introduced through the surgical incision and displaced by shifting and rotating until the target zone to be irradiated is properly delimited. While the user moves the applicator its position is continuously displayed on all the viewports (Fig. 4). It is also possible interactively to change the geometrical properties of the collimator: diameter and bevel.

Once the images adequately resemble the surgical situation, the user may enter the third mode (''Dose''), in which two possibilities for planning and dose calculation are offered. The first is to display an approximate dose distribution based on the isodose curves obtained with water phantoms for the particular applicator and energy selected (Fig. 6). The overall planning can be checked by observing the dose distribution obtained, allowing the redefinition of the collimator type, beam energy, or even surgical approach before the real intervention takes place. The second option is an exact dose calculation, obtained by creating a new data set with the edited images, which are then exported to a standard radiotherapy-planning system. This approach produces more reliable results, but it is much slower.

The approximate planning can be produced from either CT or MR images, but only processed CT images can be transferred to the standard planning system. The application can also show at any moment a 3D image generated by surface rendering depicting the relative positions of the patient and the applicator; this might sometimes be useful for better spatial visualization (Fig. 7).

Figures 2–7 represent a typical case of pancreas cancer. Simulation has us allowed to foresee the proper applicator diameter and bevel that better matched the patient's anatomy and tumor bed region, as well as the proper energy for the desired depth. In this case, the tumor bed consisted of the posterior margin of pancreas resection and included the cava vein and soft tissue of the posterior aorta. The tissues protected by mechanical retraction (Fig. 5) were stomach, liver, small bowel, transverse colon, and right kidney. This type of surgery makes use of very large surgical incisions, which allows for high mobility of the applicator. In other types of surgery (rectal cancer, for example), the bony frame of the pelvis significantly restricts this mobility, and the simulator is also useful to determine the proper positioning of the applicator.

DISCUSSION

According to the present state of the art, dosimetry for intraoperative radiotherapy relies almost exclusively on the experience of the radiation oncologists interpreting together two-dimensional static images and the standard calibration curves on water phantoms. The isodose distribution in place is just calculated from a ''mental'' process that matches the calibration curves to those images.

The software described in this paper assists radiation oncologists and surgeons in the management of complex 3D situations, allowing them to simulate the relative spatial positions of the patient and the collimator. There are two different ways of using the program: One is as a pretreat-

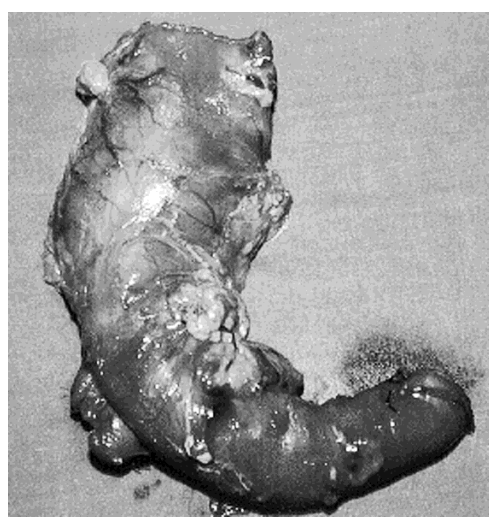

Fig. 3. Extracted organ corresponding to Figure 2 simulation.

Fig. 4. General view of the application's user interface running in Insertion mode, simulating the applicator insertion.

ment computer assistance tool that allows better planning of the intervention and gives an idea of the possible problems the physicians will have to face during the real procedure. Users can also easily simulate different alternative approaches, assessing their relative advantages and risks. The other method consists of making use of the program after the intervention, when a clear knowledge exists about how the intervention developed. In this way, obtaining the exact dosimetry is a very interesting feature, which allows for much better quality control and proper evaluation of the patient response and follow-up. It should be noticed that the program does not deal with the possible global geometric distortion that sometimes appears as a consequence of the surgery, owing to the use of surgical instruments. This is not a severe limitation; it affects mainly structures located along the trajectory (not irradiated) and not so much the tissues located immediately below the applicator. This is due to the fact that, for most of the anatomical localizations, the target structures are quite rigidly attached to the tumor bed, usually constituted by fixed surfaces close to the body bony frames. This does not hold true for some anatomical regions, such as the brain, where the absence of any stable background might allow for movements, introducing significant changes. Nevertheless, in these regions, the

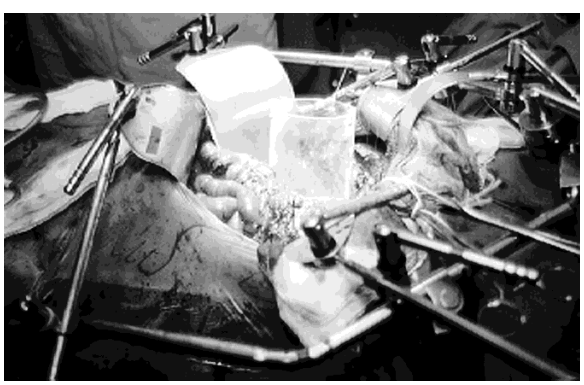

Fig. 5. Real IORT procedure: insertion of the applicator.

tool is still useful for planning. It should be emphasized that the application does not attempt to reproduce all the possible surgical manipulations, and thus is not properly a surgery simulator, but only a required intermediate step prior to dose estimation.

After initial tests performed on five patients, users have reported the approximate dosimetry tool as a useful feature for initial planning. However, results are not reliable in certain cases when the water phantom curves do not exactly fit the situation (for instance, bone structures). The water phantom data are exact enough for the simulation in all soft tissues but differ from real dosimetry when tissues with very different densities are involved. Results can also be inaccurate when blood collections appear in the beam trajectory; they can substantially modify the electron isodose distribution. The user must always be aware of the approximations involved in this fast dose estimation technique.

Transferring data to the planning system to get exact dosimetry was considered quite slow and, thus, valuable only for postsurgical precise dose control. The clinical trial is still on course for better assessment of all these points.

An obvious improvement to the approach presented in this paper would be to incorporate an algorithm for exact dose calculation, embedded in the program. However, most of these algorithms are slow, and for planning simulation speed is a key concern: Dose recalculation each time the user changes the setting renders the program almost unusable. Despite the inevitable inaccuracies discussed above, the overall impression of the clinical users is that the procedure may substantially improve the quality, reliability, and safety of IORT by allowing both more precise dosimetry and easier intervention planning. It also highlights surgery simulation techniques not only as an educational tool but also as a part of the standard treatment protocol in routine use.

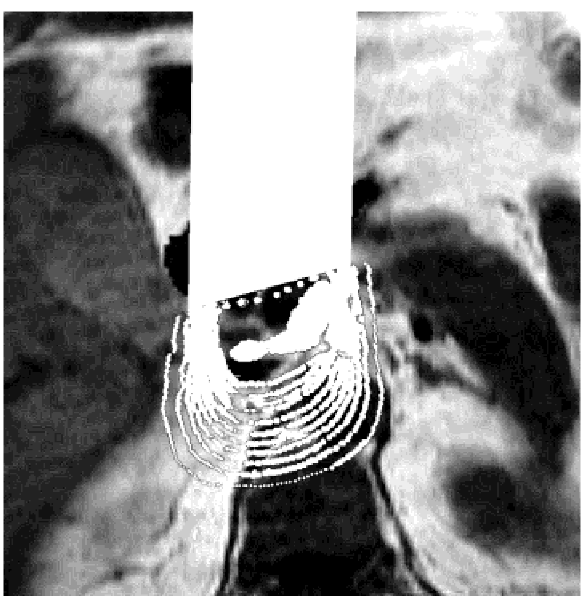

Fig. 6. Color overlay of the approximate isodose curves on the patient image.

Fig. 7. Three-dimensional rendering of the patient and the applicator.

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