Real-Time Treatment Planning Optimisation for Brachytherapy

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Abstract

In this paper, we present an integrated system for real-time dose distribution calculation and treatment planning optimisation for brachytherapy of prostate cancer, with a special emphasis on the visual integration of the dosimetry and target images obtained from the open magnetic resonance system. This system involves a fast method to calculate dose distributions of multiple concurrent radioactive sources, based on the combination of elements from a database of pre-calculated dose distribution maps for single sources, combined linearly to provide the final dose distribution map. Simulated annealing, in conjunction with the inverse planning method, is used to determine the source dwell times at pre-selected locations in order to optimally irradiate the tumour while preserving the surrounding healthy tissues. This algorithm, implemented in FORTRAN, is integrated into a computer-assisted treatment planning tool, written in JAVA, using the runtime class and *RMI API of Java. The whole system is now under clinical testing at the Geneva University Hospital.*

Keywords: medical imaging, brachytherapy, image-guided treatment, computer-assisted intervention.

1. Introduction

The term brachytherapy comes from the Greek word *brachy* meaning short. It is therefore known as a modality where an encapsulated source is held either at a short distance or placed adjacent to the treatment volume. Before 1950, brachytherapy offered a significant advantage over the existing external radiation therapy because of the use of stable and well known radium and radon sources. However, the development of the betatron, linear accelerator and cobalt irradiator, in the 1950s, offering a wide range of radiation energy and flux levels, brought up the disadvantages of brachytherapy at that time, namely thick and rigid radium sources with danger of rupture, high radiation exposure to physicians and nurses, gaseous radon production and the non-availability of precise methods for the placement of seeds in the target region. However, in the 1980s, the availability of more suitable isotopes, such as Ir-192, I-125, Pd-103 and Cs-137 as well as the development of ultrasound-guided transperineal implantation of the needles, led to better control rates and hence a wider public acceptance of brachytherapy. In the subsequent years, a lot of development has been done in the source design, as also in the use of computers to optimise the source placement and to help perform the treatment. Recent studies have shown that better results in the treatment of prostate cancer can sometimes be achieved with a combination of external irradiation and brachytherapy. In any case, it

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seems that brachytherapy will remain an important modality for cancer treatment, the decision for its use being dependent upon tumour type and size, rate of growth, location, patient preference, and physician judgement.

In this study, we propose a treatment protocol that involves an open MRI (Magnetic Resonance Imaging) system to perform accurate image-guided interstitial implantation and irradiation of gynaecological and prostate cancers. In this protocol, needles are placed under MRI control in the pelvic area and dosimetry simulated with optimal dwell times of the source at different locations using data corresponding to a standard HDR source. In order to efficiently use open MRI to perform brachytherapy under direct visual control, titanium-zirconium (Ti-Zr) MR compatible needles, Ti-Zr trocard needles, MR compatible stirrups for gynaecological positioning of the patient, templates for needle introduction and dedicated grids for accurate implantation under stereoscopic infrared guidance tools have been developed. Once satisfactory dosimetry conditions are achieved, a radioactive Ir-192 source (MS, HDR or PDR type) from Nucletron is then moved automatically (PC controlled) through the different needles to irradiate the tumour at the pre-selected positions.

2. Real time dose calculation and planning optimisation

One of the key issues in this kind of computer-assisted intervention is the planning, i.e. the definition of the optimal positions of the needles/sources and the optimal exposure times of the sources in order to best irradiate the tumour while preserving the surrounding healthy tissues as well as the surrounding tissue at risk. To find this optimal solution, we need to define an appropriate objective function (the so-called cost function) and a suitable algorithm to find an optimal solution.

The cost function is generally calculated by evaluating the dose distribution for a candidate configuration, by considering the irradiation of the tumour with respect to the irradiation of the healthy tissues. The classical way to calculate dose distributions is the well-known Monte-Carlo simulation. Unfortunately this method takes days to produce a dose distribution map, and hence can not be used in practice for planning optimisation, where this calculation has to be preformed on-line and iteratively until an optimal planning is found. Therefore a simplified solution based on the use of a 3D database of pre-calculated distribution maps for simple single sources was proposed [1]. The code MCNP release 4C [2] has been selected for this purpose. These maps corresponding to single sources are then combined linearly to obtain the dose distribution of the complete needle configuration. With this scheme, a dose distribution map for a given set of source positions and exposure times can be obtained in a few seconds. The validation of this method has been performed by (a) comparison with standard results obtained by direct Monte-Carlo simulations and (b) analysing benchmark experiments carried out on phantoms using active and passive dosimeters [3].

An optimisation algorithm is used to find the optimal configuration. In our case, simulated annealing [4] is used, with the goal to avoid local minima of the cost function and to find a global optimum. The function optimisation is based on the prescription of the clinician for all the target and peripheral regions as well as organs risk. From the optimisation scheme, a solution is defined by the dwell time (or exposure time) at each dwell position. The number of dwell positions varies for each patient, and are about a few hundreds. The dwell times are allowed between 0 and 15 seconds, with steps of 0.1 second. Thus, the space of solution is quite large.

3. Integration of dosimetry and MR images

Like many other software systems developed in (nuclear) physics, the above-described application has been developed in FORTRAN and makes an effective use of a three-dimensional experimentally validated database and an efficient dwell time optimisation scheme. We will now present how we integrated it in a complete computer-assisted treatment planning system, developed in Java.

The idea is to be able to use any application, independently of the programming language used to develop these applications, directly from a main program written in Java. Moreover the system must allow the execution of this application on a machine different from that where the principal application runs.

To solve the first point, we use the capacity of Java to launch the execution of operating system commands via the Runtime class, and to communicate with this process by means of its input and output stream. For the second point, we use the Remote Method Invocation API (RMI), which is used for the network communication. The later makes it possible to call methods of a remote object in the same way as if it were on the local machine. The conjunction of these two systems enables us to execute and communicate with any type of application on any computer present on the network.

The architecture of the total system is subdivided in four principal components.

Two on the local machine:

- The main application: including the user interface and all the tools for the intervention planning.
- A module for the management of network communications.

Two on the distant machine:

- A demon on standby, waiting for requests for calculation. This demon activates itself only at the time of request coming from the module responsible for the management of the network communications.
- A module for the execution of the application to be integrated, which provides the data and the input parameters for this application, launches its execution and recovers its results to be transmitted to the network communications management module.

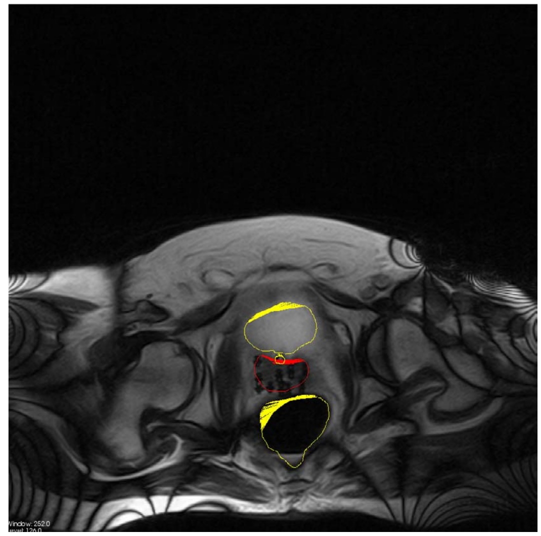
Note that neither privacy nor security issues have been taken into account since the whole system will run on the internal network of the hospital, and not between two sites. Should this change in the future, appropriate techniques like SSH and VPN will be added to the system. We now present the details of the operations.

Step 1:
The user carries out all the set-ups to the dosimetric calculation, i.e.:

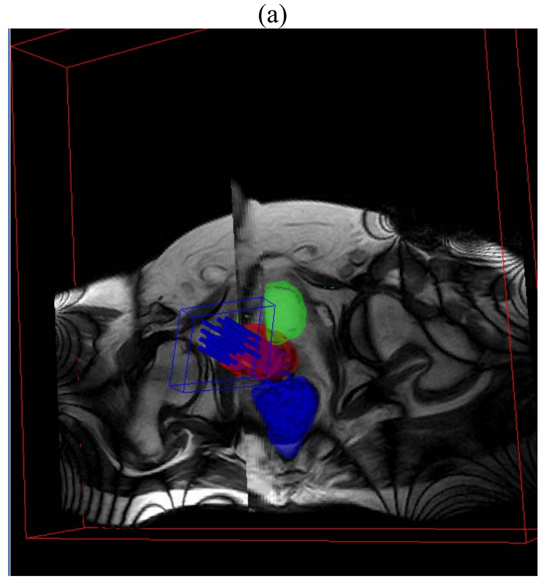
- Opening of the IM images from the disk,
- Segmentation of the organs of interests by manual drawing or semi-automatic segmentation (Figure 1a.),
- Positioning of the guide for needles implantation, on the 2D or 3D view of the scene,
- Identification of the locations of the needles to be implanted (Figure 1b.).

Step 2:
Launching of the dosimetric optimization process carried out in four steps.

The principal application generates a volume of data containing the organs of interests. It calculates the potentials positions of the radioactive sources according to the position of the needles to be implanted. Then these data are transmitted to the network communications management module (Figure 2-1).



(a)



(b)

Figure 1: (a) The segmentation of the organs of interest. (b) The selection of the locations and positioning of the needles to be implanted.

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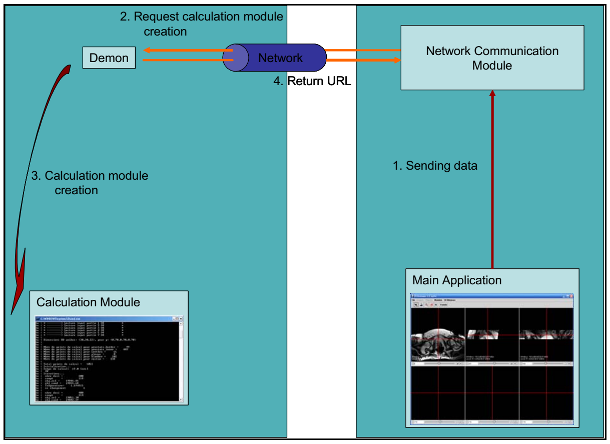

Figure 2: System architecture.

The network communications management module connects to the demon on the distant machine and asks him to create a module of calculation (Figure 2-2). Once this one is created (Figure 2-3), the demon returns its URL and goes back on standby. The management module can then connect to the calculation module, and transmit the data and configurations parameters (Figure 3-4). Once this transfer has been carried out, the order to start calculation is given. The network communications management module is then put on standby.

The calculation module writes the data and the input parameters of the dosimetry optimization application on the hard disk, then it launches the application (instruction: System.getRuntime().exec(`application.exe');). During the entire execution time of this operation, the module reads its standard output (Figure 3-4). This output can be redirected towards the main application. When the application finished its optimization, the module reads the files of results and sends them to the module for the management of network communications. Once this transfer carried out, the module finishes (Figure 3-6).

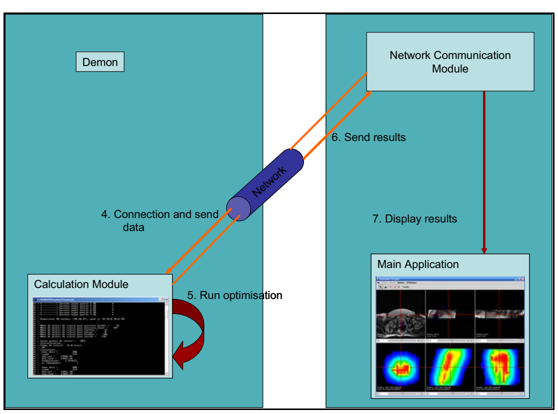

Figure 3: System architecture (cont.).

At the side of the local computer, the network communications management module receives the results and transmits them to the principal application (Figure 3-7) which will make it possible to the user to visualize them and to treat them (Figure 4. and 5.).

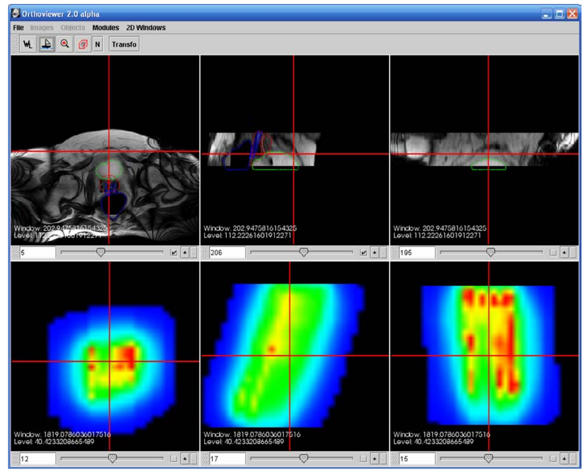

Figure 4: The MR images and the optimized dose map.

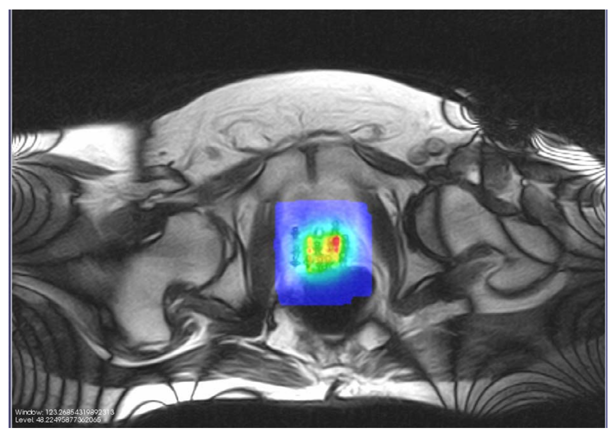

Figure 5: The fusion of MR images and optimized dose map.

When this operation is completed, the radio-oncologist has a proposal for optimal planning in his hand. He now has to realize this planning. On our system, the needle placement is assisted by tracking the 3D position and orientation of the needles thanks to an optical tracking system (the POLARIS system, NDI, Waterloo, Canada), interfaced with our platform. The actual position of the needle is displayed on the screen, superimposed on the optimal position (like on figure 1(b)), so that the physician can perform his operation exactly according to the optimal planning.

The major advantages of this platform are the possibility to integrate heterogeneous applications independently of the programming languages used, its independence of the operating systems and the possibility to distribute calculation on several machines. Moreover, the distant computer may be a cluster.

This system is now installed at the Geneva University Hospital and is under final tests. We are now investigating in details the performances of such system. In the future, a parallel implementation will be considered if needed.

4. Conclusions

We have presented here a method for real-time dose calculation and planning optimisation, with its integration in a complete computer-assisted planning system for prostate cancer brachytherapy. Its architecture is composed of two modules, one taking care of the graphical user interface, data handling, intervention realisation (object tracking) and network communications, and the other ones on the real-time calculation of irradiation doses. The first module is written in JAVA using the VTK library and the second one in FORTRAN. The communication between both modules is done through the JAVA RMI API. Once the current tests will be found satisfactory, the complete package will be released for routine use at the Geneva University Hospital. Further work will include more investigations on the optimisation problem, as well as its extension to the treatment tumours of other organs.

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