DETERMINATION OF OPTIMAL BEAM POSITIONS FOR CONFORMAL RADIOTHERAPY

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ABSTRACT

The Intensity Modulated Radiotherapy (IMRT) is a technique currently under development for the treatment of carcinogenic tumours, whose main objective is to concentrate the radiation dose in the tumour limiting the dose received by adjacent healthy tissue. The treatment by means of IMRT uses a discreet set of spatially distributed beams of radiation. Habitually, the radiation beams are placed separated with a fixed distance in the space around the patient, although sometimes the radiotherapist sets their position based on his own experience.

In this article a new method is offered to determine the optimal position of the radiation beams, in such a way that the geometry of the patient is considered and the required dose in the different organs. The selection of positions is based on the study of a Figure of Merit (FoM), that allows the dose to be evaluated that the patient will receive. The proposed method has been applied on a real case of cancer, where the results obtained demonstrate a greater effectiveness in the treatments when considering the positioning of the beams according to the proposed method.

1. INTRODUCTION

The Intensity Modulated radiotherapy (IMRT) is a technique applied to the treatment of the cancer that uses high power X-ray beams, spatially located in different positions around the patient [1].

The purpose of this technique is to obtain a dose distribution in the patient that allows the tumour to be eliminated without damaging the adjacent healthy organs.

The planning of the radiotherapy treatment requires the determination of the intensity patterns that each beam must provide in order to obtain a determined dose distribution, and in such a way that radiation dose obtained the volume corresponding to the tumour (CTV : clinical target volume) is as close as possible to the prescribed one, without exceeding the values of maximum established dose for the adjacent organs at risk (OAR : organ at risk).

This process demands the analysis and resolution of an inverse problem [2], considering the entrance parameters : the geometry of the patient (size, shape, type and location of the organs), the prescribed dose by the radiotherapist for each organ, and so the positions for the radiation beams. Treatment is carefully planned by using 3-D computed tomography (CT) images of the patient [3].

There are different works that analyse the problems of the number and the position of the radiation beams [4] [5]. Some of them conclude that the right choice is to consider 5 beams angularly distributed around the patient. In other cases, the radiotherapist is who decides the spatial location of the beams by means of his own experience and depending on the type, size, shape, and location of tumour.

In this work, a new method is proposed based on the establishment of a function of merit that allows the optimal position of the radiation beams to be obtained considering the particular geometry of each patient.

2. BACKGROUND

The radiated intensity by each beam is not uniform, and it can be described by a fluency matrix whose elements represent the amount of radiation in a particular spatial direction (figure 1).

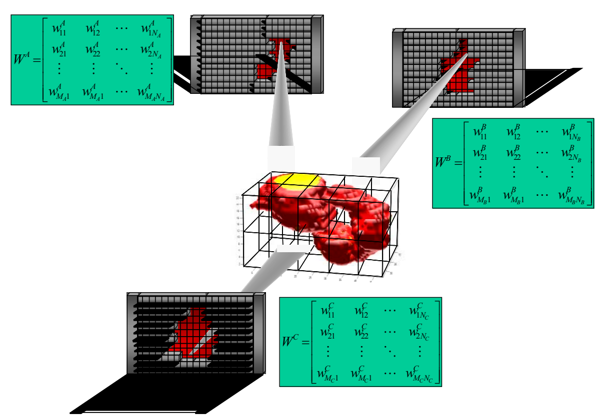

Fig. 1. A schematic diagram to model a inverse planning with three beams.

Firstly, we will evaluate the amount of dose contributed by each beamlet to the patient considering a model of primary radiation. The total dose in each voxel of the patient will be calculated as the sum of the contribution of the dose of each of the radiation beams.

The principal idea of the work is to determine, by establishing of a figure of merit, those beams most suited for a specific treatment of radiotherapy. We will calculate the trajectory of the different beamlets where each beam is divided and we will consider the intersection of these beamlets with the volume corresponding to the CTV and with the corresponding one to the organs at risk. The aim is to form a set of beams in order to allow us to obtain the dose closest to the prescribe one and to minimize the dose received in the organs at risk.

To model the dose by the patient to each voxel:

$$D_n = \sum_m k_{nm} \cdot w_m \tag{1}$$

Where D_n is the dose delivered to voxel *n, k_{nm}* is the attenuation suffered by the beamlet *m* from the focal point to the voxel *n* in the interior of the patient, and w_m is the weighting of the beamlet *m*. The previous mathematical expression can be expressed in a matrix form by the following expression:

$$\begin{bmatrix} D_1 \\ D_2 \\ \vdots \\ D_n \end{bmatrix} = \begin{bmatrix} k_{11} & k_{12} & \cdots & k_{1m} \\ k_{21} & k_{22} & \cdots & k_{2m} \\ \vdots & & \ddots & \vdots \\ k_{n1} & \cdots & \cdots & k_{nm} \end{bmatrix} \cdot \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_m \end{bmatrix} = K \cdot w \tag{2}$$

Each element of the matrix K is calculated by means of the following expression:

$$c \cdot \frac{1}{r^2} \cdot e^{-\mu h} \tag{3}$$

r is the distance from the focal point to the patient's skin (m); *h* is the distance from the patient's skin to the voxel (mm); μ is a attenuation coefficient of the patient (mm^{-1}). However, dose calculations are often performed by using Monte Carlo simulation codes in many other works.

A procedure to estimate the optimal positions of the radiation beam could consist in solving the planning for all the sets of possible beams and to choose the set of beams that will provide the best results. This option is not viable due to the high computational costs that entail high run times.

In the following lines a new method is described that allows a fast estimation of the weightings, providing approximated values for the fluency matrices for the values that would be obtained solving the planning of the treatment.

3. BASIC CONCEPT OF THE METHOD

The idea is to evaluate the dose contributed by each beamlet in each voxel, thus to determine the suitability of each beamlet. For this reason a study of the trajectory of each beamlet is made, analysing the intersection of the beamlet with the organs at risk and the tumour. Once the trajectory of the beamlet is determined, the following expression is proposed to estimate the figure of merit of each beamlet m:

$$FoM(m) = \frac{\left(\sum_{n \in \mathrm{CTV}} P_n \cdot d_{nm} \cdot \Delta t_{nm} \right) / \left(n^{\mathrm{o}}\_vox\_CTV \right)}{1 + \left[\left(\sum_{i=1}^{num\_OAR} \sum_{n \in \mathrm{OAR_i}} P_n \cdot d_{nm} \cdot \Delta t_{nm} \right) / \left(n^{\mathrm{o}}\_vox\_OAR_i \right) \right]} \tag{4}$$

Where P_n is a variable used to determine the priority of the different patient tissues. This variable can be configured by the user in each execution of the IMRT system in order to obtain specific results depending on the characteristics of the patient; d_{nm} is the dose contributed by the *m* beamlet to the *n* voxel supposing his weight equal to unity. This dose will be calculated using expression (3).

Δt_{nm} is the length of interception of beamlet *m* with voxel *n*.

The figure of merit is normalized dividing the terms of each organ by the number of voxels corresponding to the same organ. The subscript *i* is due to the possible existence of different organs at risk.

The constant *Off* is added to the figure of merit for those beamlets that intercept voxels of the tumour to obtain greater uniformity in the tumour:

$$FoM(m) = \begin{cases} FoM(m) + Off & FoM(m) > 0 \\ 0 & FoM(m) = 0 \end{cases} \tag{5}$$

A high value of *Off* means a more uniform dose in the CTV but high doses at the organs at risk are obtained.

The figure of merit allows each beamlet to be evaluated, that is to say, it allows to find out which beamlets are more suitable to irradiate the tumour avoiding damage to tissues sensitive to the radiation. A high value of the figure of merit will mean that the corresponding beamlet must contribute a great amount of radiation. Therefore, the values obtained for the figure of merit can be considered as the estimated weightings for each beamlet [6].

In this way, we can obtain the dose contributed by each beamlet considering the weightings as the values of the FoM in expression (1).

4. BEAM SELECTION PROCESS

Once the figure of merit has been defined, we establish a set of possible beams of radiation which are candidates to be chosen, considering beams defined with an angular separation of 10º. This group will be called the *Test* group. The aim of the work consists in selecting the best combination of beams from these candidate beams in such a way that they provide the best solution for the dose distribution on the patient.
The group of selected angles will be denominated *selected* group. The number of beams of radiation or number of angles that form the *selected* group will be determined by the user.

Firstly, we will select a set of angles from the *test* group at random to form the *selected* group. The worse beam of the group will be selected and this beam will be replaced by an angle from the *test* group in an iterative way in order to minimize the error function for the *selected* group, which is described later.
The iterative process to determine the most optimal angles and thus to form the definitive *selected* group is formed by the following steps:

1- The total dose contributed by the *selected* group is calculated by means of expression (1) considering the figure of merit of each beamlet as their corresponding weighting.

2- The error for the dose obtained by the set of angles *selected* is calculated using the following expression:

$$Err_{sel} = \sum_{n} \begin{cases} T \cdot \left(d_n - d_p\right)^2 \; if \;\; n \in CTV \\ d_n^{\,2} \;\; if \;\; d_n > d_p \;\; and \;\; n \in OAR \\ 0 \quad if \;\; d_n < d_p \;\; and \;\; n \in OAR \end{cases} \tag{6}$$

where d_n is the obtained dose (the sum of the dose contributed by each beamlet) at the *n* voxel. d_p is the prescribe dose; T is a constant to give a determined priority to the tumour.

3- The beam that contributes least in reaching the optimal dose at the CTV keeping the restrictions at the organs at risk is determined from the *selected* group by means of the following function:

$$Err_{u \in selected} = \sum_{n} \begin{cases} T \cdot \left(d_n - d_p\right)^2 \cdot d_{nu} & if \;\; n \in CTV \\ d_n^{\,2} \cdot d_{nu} & if \;\; d_n > d_p \;\; and \;\; n \in OAR \\ 0 & if \;\; d_n < d_p \;\; and \;\; n \in OAR \end{cases} \tag{7}$$

d_{nu} is the dose provided by the set of beamlets of the beam *u* in voxel *n*.

4- Once the worst beam is selected in the previous step, this beam is replaced by each beam of the *test* group calculating the error of each formed group using the expression used in step 2. That angle from the *test* group that obtains the lowest error function will be the chosen to replace the selected angle in step 3 to form the *selected* group.

5- The replacement of the selected angle corresponding to the *test* group (step 4) by the selected one in the *selected* group (step 3) is made if the function of error obtained with the angle coming from *test* group is smaller than the one obtained in step 2.

6- Step 1 is returned to and a new iteration begun. The iterations continue until the beams of the *selected* group do not change.

Once the most beneficial angles are determined, the solution of the inverse planning can be determined calculating the corresponding weightings for each beamlet.

5. RESULTS

In this section the results are shown for the proposed method, in order to select the optimal positions of the radiation beams in a IMRT treatment.
A real case of prostate cancer is considered. The volume affected by the tumour comprises of the prostate (CTV), the rectum (OAR1), the bladder (OAR2) and unspecified healthy tissue.

The results are shown by dose/volume histograms (DHV) which represent the percent of volume of each organ that surpasses a certain percentage or level of dose.
The prescribed doses are: 70 Gy for CTV, 3 Gy for bladder and 10 Gy for rectum.

In figure 2 the histogram obtained is shown for different organs considering 5 equiangular spaced beams around the patient (36º, 108º, 180º, 252º, 324º). The positions obtained for radiation beams using the proposed method are 70º, 90º, 110º, 130º, 190º. The calculated dose executing the planning with these positions is shown in the figure 3:

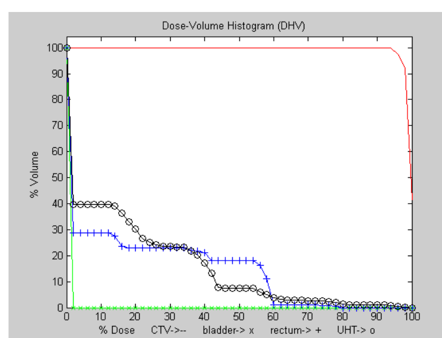

Fig. 2. DHVs for the CTV and OARs with five equiangular spaced beams.

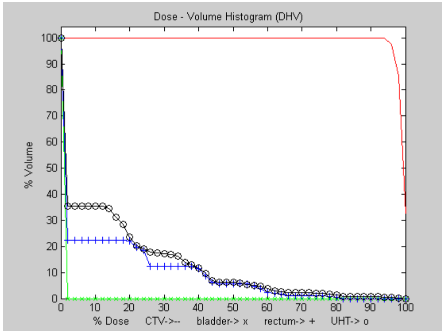

Fig. 3. DHVs for the CTV and OARs with five beams for the proposed method.

From the analysis of these curves, it is easy to observe that the results obtained using the calculated beam positions by our method produce an important improvement on the treatment because the received dose by the rectum and by the unspecific healthy tissue is noticeably less than the dose obtained by means of equiangular spaced beams.

The same priorities (P_n) in the treatment have been considered in order to make these comparisons (75% for CTV, 15 % for OAR and 10 % for unspecific healthy tissue). The results considering 4 radiation beams are shown here: Figure 4 shows the histogram obtained using 4 equiangular spaced beams (0º, 90º,180º,270º)

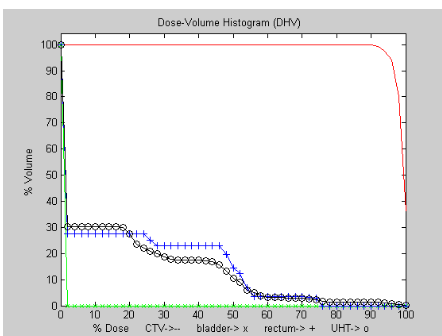

Fig. 4. DHVs for the CTV and OARs with four equiangular spaced beams.

The results obtained considering the calculated beam positions by our algorithm for the case of 4 radiation beams (70º, 90º, 110º, 130º) are shown in the figure 5: In this case the relative improvement is greater than the improvement obtained using 5 beams. This is due to the number of beams used. If we use a low number of beams, their position is more important than in the case where the number of beam is greater.

On the other hand we can see that the results obtained placing 4 beams in optimal positions (figure 5) are much better than the results using 5 equiangular spaced beams (figure 2).

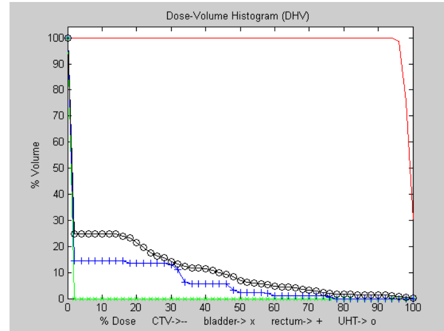

Fig. 5. DHVs for the CTV and OARs with four beams for the proposed method.

6. CONCLUSIONS

At the moment the position of the beams is determined either by the radiotherapist or these beams are spatially distributed around the patient by means of a fixed separation angle. In this article, we show the advantages of employing optimal beam positions in the planning of intensity modulated radiotherapy for the treatment of cancer. The proposed method allows to obtain a set of positions for radiation beams, depending on the specific geometry of each pacient, in such a way that we reach the prescribed dose in the CTV, and minimize the dose received in the organs at risk. In addition, the execution time of the algorithms is about a couple of minutes, allowing to use this method like a previous step of planning process.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

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