STUDIES OF FIELD SHAPING WITH "OMOIOTHETA" BEAM MODULATORS IN ROTATIONAL RADIATION THERAPY

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Abstract: This paper presents a development of a software tool for modeling of "omoiotheta" beam modulators (OBMs) and their subsequent application in studies of intensity modulation in rotational radiation therapy. "Omoiotheta" protector is a diminished copy of the corresponding Organ At Risk (OAR) and it rotates so, that the OAR is always in a shadow of it during gantry rotation. The "omoiotheta" shapers reduce excessive irradiation of the Planning Target Volume (PTV) and make dose distribution more uniform. A case of a tumor near the spinal cord was chosen for our studies. Developed software tool calculates location and dimensions of the OBMs, using information about the parameters of OAR as input. The verification of the software tool showed good agreement between experimental and simulation data. The results of the simulation studies of intensity modulation with OBMs using both solid-geometry and voxel models showed that rotational therapy with OBMs offers adequate protection of the OAR and uniform dose in the PTV.

Introduction

Rotational radiotherapy with gravity-oriented devices, first developed and reported in the 60's,[1] is one of the alternative methods of the three-dimensional conformal radiation therapy (3D-CRT). In this technique the OAR is shielded by an absorber of a similar shape, which preserves its orientation parallel to the OAR during the rotation due to the gravity. This technique offers following advantages: 1) significant protection of the OARs and conformal shaping of the field,[1-3] 2) use of inexpensive and easy deformed materials (like lead, Cerrobend, lead-shot and steel-shot)[2] and 3) no need to change the filter for each gantry position. However, the use of the gravity-oriented devices is accompanied by several inconveniencies, like the manufacturing of the beam modulators and large space that is necessary for their storage.

Generalizing the principles of gravity-oriented devices, in this paper we present the development of software tool for design of "omoiotheta"[*] beam modulators (OBMs) and it's verification as well as studies of beam shaping with OBMs in rotational 3D-CRT. "Omoiotheta" is a compound word of the Greek words "omoios" that means "same, similar" and "thesi" that means "position". In other words, the beam modulators stay in similar position with the OAR and remain parallel to themselves during the gantry rotation. The studies were performed for a case of a tumor, located near the spinal cord, with protection of the spinal cord during an irradiation. In-house developed Monte Carlo (MC) based Radiotherapy Simulator (MCRTS)[4] was used to simulate the irradiation transport.

[*] For the first time the term was used by Proimos et al[3]

Materials and Methods

A. Principles of "omiotheta" beam modulators

For the sake of clarity, OBMs were divided in two categories, according to their function: "omoiotheta" protectors and shapers. The protector P is attached to a shaft A that rotates synchronously with a source around the axis of rotation, as shown in Fig. 1. During gantry rotation a line AP, connecting the centre of the protector and its shaft, remains parallel to a line CO, connecting the isocenter and the center of the OAR. Protector is a miniaturized copy of a corresponding OAR and is placed at a certain distance from the source, where beam eye's views of the OAR and the protector coincide. Thus the OAR is in the shadow of the protector during whole rotation.

Protector, inserted into the treatment beam, markedly affects the uniformity of the dose outside the shielded region.[5] In order to stop the increase of the

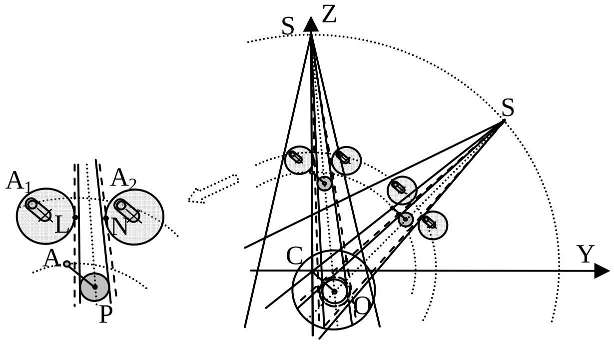

Figure 1: Use of the OBMs in rotational radiotherapy. The following labeling is used: S– source, P– protector, A– shaft of the protector, A1 and A2– shafts of the shapers, C– isocenter, O– center of the OAR and LN– width of unshaped beam. The collimator has been omitted for clarity.

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dose outside the protected region, the outer layers of the beam have to be filtered additionally. "Omiotheta" beam shapers (circular disks of appropriate material and diameter)[6] are used for this purpose. The shapers are attached to the shafts A_1 and A_2 that are parallel to the axis of rotation and rotate synchronously with the source, as illustrated in Fig. 1. Both shapers keep their direction parallel to the initial. The drawback of the additional field shaping is that the dose in the PTV is reduced.

B. Neck models

Solid-geometry (mathematical) and voxel (tomographic) neck models were used in our work.

A solid-geometry neck model was composed of a cylindrical object with another cylinder of smaller diameter (OAR) inserted in its centre. The diameters of the cylinders were 15 and 2.4 cm respectively.

A realistic voxel neck model was created using CT images, taken from the National Library of Medicine's Visible Human Project®, with their further transformation to voxel based geometry. The original CT data consisted of axial CT scans of the head taken at 1 mm intervals at a resolution of 512×512 pixels. The central part of a 3D matrix with useful information, $250 \times 250 \times 100$ in dimensions with voxel size $1\times1\times1$ mm^3, was used. Physical properties, such as tissues density and composition were assigned to each voxel, according to the work of Schneider et al.[6] The protected region diameter was chosen to be 1.6 cm.

C. Calculations of the geometrical parameters of OBMs

The linear dimensions of the protector have to be $\frac{SA}{SID}$ times the dimensions of the corresponding OAR, where SA is source-to-shaft (according to Fig. 1) and SID– source-to-isocenter distance. The coordinates of the protector can be determined, using simple geometrical computations and keeping in mind that OAR must coincide with the shadow of the protector.

Dimensions and material of the "omoiotheta" shapers were calculated, as described in the literature:[2]

1. State the diameter of the dose built-up annulus (d_{bup}), i.e. the region which will not be additionally attenuated by shapers, using the central dose profile of the rotating beam, modulated only by an "omoiotheta" protector, in the plane perpendicular to the axis of rotation;
2. Find the distance between the shapers (the width of the unfiltered beam): $LN = d_{bup}\left(1 - \frac{z_{shaft\_shapers}}{SID}\right)$, where $z_{shaft\_shapers}$ is the z-coordinate of the axis of the shaft, to which shapers are attached (see Fig. 1);
3. Calculate the diameter of the shapers: d = A_1A_2-LN;
4. Calculate the average chord length (aver_chord) of the beams passing through the shaper that give the maximal dose in the PTV for the whole rotation of 360°.
5. Calculate the linear attenuation coefficient: $\mu = -\frac{\ln(I/I_0)}{aver\_chord}$, which actually is weighted-mean value of polyenergetic spectrum.
6. Find the material, which corresponds to the received linear attenuation coefficient μ.

D. Irradiation setups:

1. solid-geometry model

Two arrangements were used in the case of the solid-geometry model investigations. In the first one, the isocenter coincides with the centre of the OAR, whereas in the second arrangement the isocenter was shifted 25 mm relatively to the centre of the OAR along the Y axis (CO= 25 mm).

2. voxel model

For the irradiation of the PTV the isocenter was chosen to be 32 mm anterior and 3 mm to the left relative to the centre of the spinal cord. The combination of the voxel phantom and solid geometry OBMs was used for simulation.

The photon fan beam, originated from a point source of size 1×1 mm^2 100 cm away from the isocenter, was used in all experiments. For the MC simulations, the electron and photon cut-off energies were set to 0.1 and 0.01 MeV respectively. Production of bremsstrahlung photons and knock of electrons were considered for energies above 0.01 MeV. The fractional energy loss step was chosen to be 4% for the simulations with solid-geometry model and 10% with voxel model. The dose matrix was defined with $2 \times 2 \times 2$ mm^3 voxel resolution.

E. Software module

In order to facilitate the computations of the geometrical setup of the "omiotheta" beam modulators, a software application has been developed. A screen shot of the interface is depicted in Fig. 2. This tool uses

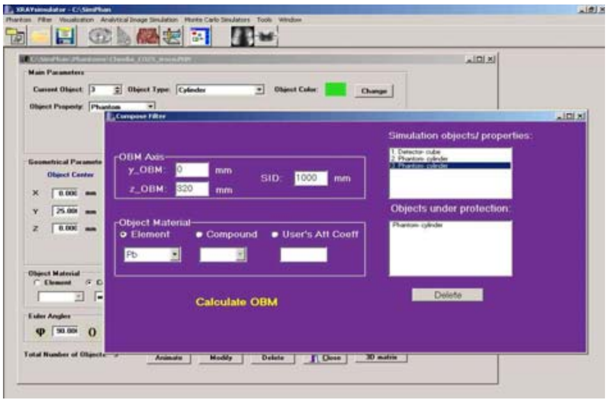

Figure 2: A screen shot of the software tool for calculations of the coordinates of OBMs for radiotherapy simulations.

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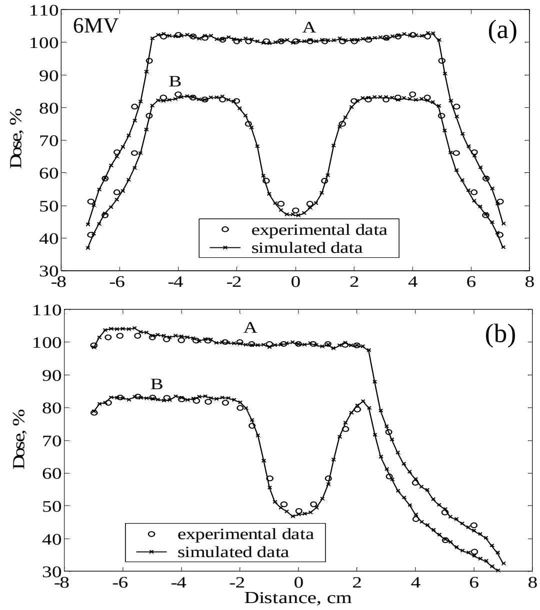

Figure 3: Comparison of simulated and experimental data for the irradiation setups, when the isocenter coincides with the center of the OAR (a) and when they are shifted 2.5 cm relative to each other (b). The curve A represents transverse dose profile at the center of the cylindrical neck model of open beam; curve B- of the beam, modulated with OBMs.

geometrical relations to calculate precise location and dimensions of the OBMs, using information about the shape, size and position of the protected organ or area at risk (OAR) as input.

The organ, to which protection has to be provided, is chosen from the list of the objects, that comprises the phantom under irradiation. Further on, this module was integrated into the existing MCRTS,[4] which was used to simulate the beam transport and compute 3D dose distributions in our work.

Results

A. Verification of the developed OBMs calculation tool

Verification of the developed OBM calculation tool was performed by a comparison of the results of our simulations with published experimental data[2]. A photon beam, collimated to a 10×10 cm^2 field size at the isocenter. Two irradiation setups, as described above, were performed. The gantry rotation was performed from 0° to 358° with discrete step of 2 degrees. A 6 MV polyenergetic beam (ELECTA SL75-5) was used to obtain experimental and simulated dose distributions. The latter was received using 4.4×10^9 photon histories.

Fig. 3(a, b) presents the comparison of simulated and experimental dose profiles for two irradiation setups respectively. The dose values were normalized to the dose at the isocenter for the open beam. The results of both irradiation setup arrangements show maximal discrepancies of 9%, 4.5% and 2%, observed at the edges of the irradiated field area, the OAR edges and the PTV plateau, respectively. The dose in the protected region is in the range of 47% to 52%.

B. Studies of intensity modulation with OBMs

1st study: with and without the "omoiotheta" beam shapers

Two simulation studies were carried out with: i) an "omoiotheta" lead protector only and ii) a complete OBMs assembly. A polyenergetic beam of 6 MV with 2.6 x 10^9 incident photons was used to simulate particle transport through the solid-geometry neck model. The gantry rotation, the field size and irradiation setups were defined identically to those in the verification experiments.

Fig. 4(a, b) show transverse dose profiles of an open beam (profile A), a beam, shaped by the "omoiotheta" lead protector (profile C) and beam, shaped by the whole OBMs assembly (profile B) for both irradiation setups. The results of this study show identical protection of the OAR for the irradiation with a single protector or with complete OBMs, while the uniform dose in the PTV is received in the case of beam shaping using the complete assembly.

2nd study: application for the voxel phantom

A voxel model, described above, was irradiated with a 6MV polyenergetic beam comprised of a total of 5.2×10^8 photons, collimated to a filed size of 8×8 cm^2 at the isocenter. The beam was modulated by the OBMs. A complete rotation of the gantry from 0° to 350° with discrete step of 10° was applied.

The degree of conformity and homogeneity of the computed dose distribution is demonstrated in Fig. 5(a, b, c). The isodose curves are expressed as a percentage

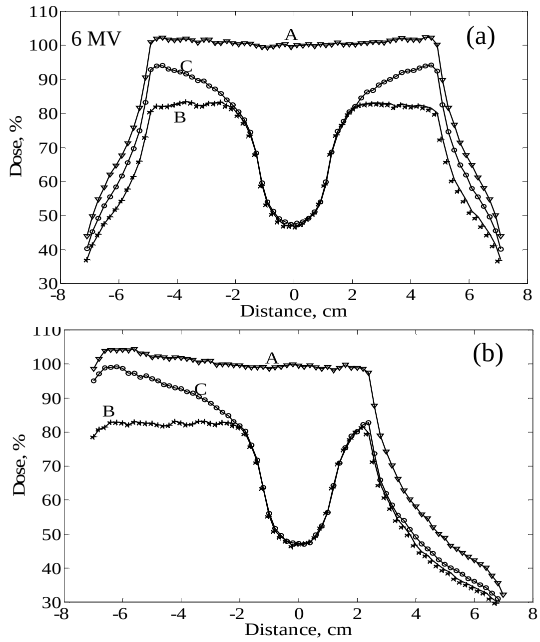

Figure 4: Beam shaping with OBMs in rotational therapy for the cases, when the isocenter coincides with the center of the OAR (a) and when they are shifted 2.5 cm relative to each other (b). The curve A represents transverse dose profile at the center of the cylindrical neck model for open beam, curve B- for the beam, modulated with "omoiotheta" protector and shapers and curve C- for the beam, modulated only with "omoiotheta" protector.

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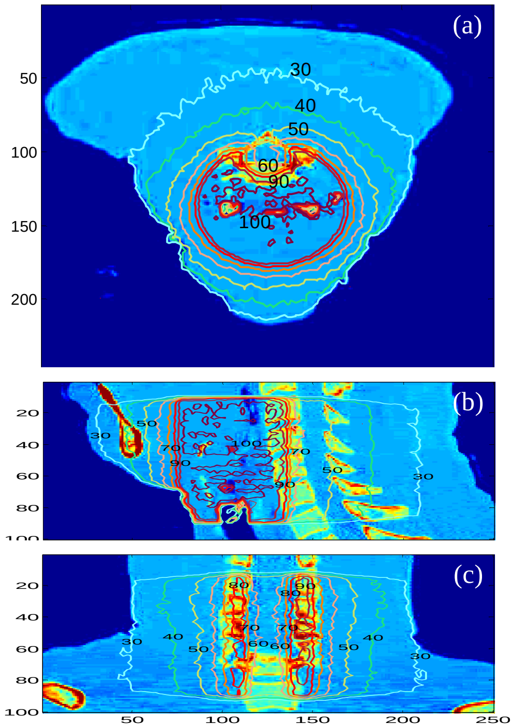

Figure 5. Isodose curves of ratational therapy with OBMs, superimposed on sagittal (a), coronal (b) and transverse (c) cross-sections of the voxel phantom. The dose curves are expressed as a percentage of the dose at the isocenter.

of the dose at the isocenter. As it can be seen, the dose values for the OAR are eliminated to 64%.

Discussion

The verification of the developed software tool for the calculations of the parameters and location of the OBMs gave acceptable results. The discrepancies in the PTV were not higher than 2%. The biggest discrepancies with the experimental data are at the regions with high dose gradient: just outside the OAR and at the field edges. The measurement of the dose in such areas, within a steeply falling penumbra, with large detectors can give serious inaccuracies.[7]

The studies of the intensity modulation by OBMs showed that the lead cylinder, "omiotheta" introduced in the beam, leads to a dose reduction of 47 to 52% of the dose of the open beam at the isocenter and ensures sufficient protection of the OAR, independently if it's used with or without shapers. A uniform dose outside the protected region is obtained, using the "omiotheta" beam shapers additionally, as the results of the 2nd study show.

The OBMs application in the rotational radiotherapy, using a voxel phantom, showed that such treatment can provide acceptably uniform irradiation to the target volume without exceeding dose tolerances for the nearby critical structures, like as the spinal cord. Usually treatment doses in the range of 70 Gy are needed, whereas the spinal cord dose should not exceed 45 to 50 Gy,[8] which is 64 to 71% of the curative dose. The maximal spinal cord dose was limited to these values.

Conclusions

In this paper we presented the implementation and validation of a software tool for design of OBMs for rotational therapy. Studies of beam shaping with OBMs for the cases of a spinal cord protection during treatment of a neck tumor showed comprehensive and adequate protection for every gantry angle and uniform dose in PTV.

Further on, it is worthy to point out several advantages of using this technique, including avoidance of hot spots and use of inexpensive materials.

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