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Title:
High resolution Brachytherapy with Lorensen and Cline's Marching Cubes algorithm

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I humbly dedicate this work To

My Father, *M.M. Alemi, MD.*, the ethical code of conduct

My Mother, *F. Taheri, MS.*, the shining spritual candle

My Professor, *D. J. Emami, MD.*, the perfect idol

My Wife,*N. Bayat, MD.*, the everlasting love and inspiration

And,

My Sister, *Aida,* the one and only.

Title Page

The manuscript Title: **High resolution brachytherapy with Lorensen and Cline's Marching Cubes algorithm**

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150 word Abstract:

Purpose: A modification is proposed to the Marching Cubes (MC) algorithm to increase the resolution of brachytherapy planning.

Materials and Methods: The four stages were dose calculation, localization, modifying MC, and OpenGL rendering. Testing was done by comparing the 6Gy Pear-Shaped Volume (PSV) over the Gross Tumor Volume (GTV) for stages IB1, IB2, IIB, and IIIB of cervical cancer. Doses to point A, bladder, three points in rectum, and the plan time were calculated and compared.

Results: Dose calculation precision was 0.001 Gy, with a speed of 3 MIPS. Localization maximum error was 0.03cm. The modified MC algorithm reached a speed of 100,000 triangles pre second, and OpenGL showed real-time performance. The GTV coverage was improved by 2-12%. Bladder showed 15-33% reduction in dose, but rectal point doses were almost identical, with only 2-7% improvement.

Conclusion: The system improves the quality of brachytherapy planning. Teletherapy should be added for stages IIB and IIIB

Author Keywords: Cervical Cancer, Intracavitary brachytherapy, polygonizing scalar fields, 3D Dose visualizations, three-dimensional treatment planning.

Abstract:

Purpose: We introduce a modification to Lorensen and Cline's Marching Cubes algorithm that increases the resolution and quality of brachytherapy planning. The shortcomings of the point-based method now used in many centers can be overcome by devising a fast and efficient system that combines different areas of science to enhance the productivity of the caring physician.

Materials and Methods: the system was developed in four stages. First, a dose calculation component was developed and optimized to compute a large number of evaluations in the shortest amount of time. Next, a source localization system was produced to acquire the geometric specification of sources and points of interest. Then the Marching Cubes algorithm was modified to allow for rapid calculation of iso-surfaces encompassing a given and changing threshold value. Finally, OpenGL standard was employed to render the results in 3D space. The system was tested by comparing the coverage for 6Gy Pear-Shaped Volume (PSV) over the Gross Tumor Volume (GTV) for stages IB1, IB2, IIB, and IIIB of cervix cancer using the conventional empiric method and the proposed customized method. Doses to point A, bladder, and three points in rectum were also calculated and compared for each method, along with the time required to plan in each case.

Results: The dose calculation algorithm achieved a precision of 0.001 Gy, and a speed of 3 million points per second. The source localization system showed an accuracy of 99.6%, with maximum error of placement less than 0.03 cm. The modified Marching Cubes algorithm re-calculated new threshold values with a speed of 100,000 triangles per second, achieving a zero response time in practical situations. OpenGL implementation would render, move and rotate the geometry in real-time.
The coverage volume was 99% for stage IB1, 95% for IB2, 88.2% for IIB, and 85% for IIIB stages, showing an improvement of 2-12% in GTV coverage. More importantly was the dose to bladder which showed 15-33% reduction because of better sculpture of the dose distribution. The two methods showed almost identical results in dose to rectum, with only 2-7% reduction in favor of the proposed system.

Conclusion: The proposed system improves the quality of brachytherapy planning, and can result in more active involvement of the caring physician in the management of patients. The lower results for stages IIB and IIIB indicates the need of adding external beam radiation therapy to the treatment.

Introduction

Intracavitary brachytherapy is a very important part of treatment in many types of cancer, including and mostly, the carcinoma of cervix[1]. Logic follows that accurate planning and reporting of the techniques used, so that they can be reviewed and reproduced later, is of outmost importance[2]. Historically, and in most instances today, the plan is reported in terms of dose to point A[3]. This approach, however, has been a subject of much debate[4], and there have been numerous additions and modifications to it[3].

The International Commission on Radiation Units and Measurements (ICRU) has recommended a system in its 38th report that relates the dose to the target volume, instead of a specific point[6], defining a now well known and popular protocol to record the patient's brachytherapy plan[5].

The fact, however, that has mostly been neglected in brachytherapy planning is that all of these systems are concerned with a finished plan, and none helps the radiation oncologist and physicist in their endeavor to achieve an acceptable plan. The most important issues in planning for cervical cancer brachytherapy include assuring adequate doses to cervix and parametral tissues while avoiding excess dose to rectum and bladder[7] with a reasonable amount of toil.

Computer aided planning is now commonplace in deciding on the best configuration and sequence of radioactive sources to be placed in remote afterloading systems[8]. What this software programs actually do is to simulate the dose distribution in the 3D space around the proposed configuration so that the radiation oncologist and physicist can decide between the various options available in this regard.

Most of the current systems present the dose in orthogonal views, which are far less intuitive than that of perspective or orthographic 3D representations of dose distribution that are seen mainly in the teletherapy planning systems.

The "Marching Cubes" algorithm, developed by Lorenson and Cline, has long been tested in high resolution 3D reconstruction of CT scan and MRI pictures[9]. This algorithm creates triangular models of constant density surfaces from 3D Medical data[10], so different tissues that produce different values in CT or MRI images can be traced and rebuild in 3D environment[10,9]. It is therefore logical to use this algorithm in visualization of the target volume. Moreover, the grid nature of the algorithm makes it quite easy to calculate the volume embraced by any given isodose value.

Marching Cubes has its own limitations and shortcomings[11]. Most of these refer to the problems of ambiguity[12], but there is also the question of huge amount of memory and large number of calculations needed for this process that can render its use in planning impractical[9]. We have devised methods to speed up the process so that it can be done in real time and have tested the results to ensure consistency and accuracy.

Material and Methods

Brachytherapy dose calculation algorithm was taken from ICRU report 33 [2,5], which calculates the Dose to a given point p which is r cm away from a point source of radiation with activity of A and Exposure Rate Constant of Γ from the following equation:

$$\mathbf{D_p = (A\,\Gamma / r^2)\, f_{med}\, C_{(r)}}$$

Where $C_{(r)} = e^{-ur}$ in which μ is the linear attenuation coefficient of the tissue and f_{med} is the correction factor that converts Roentgen exposure to cGy of absorbed dose.

A Selectron LDR brachytherapy device is in use in our ward. It uses ^{137}Cs pellets which are exceptionally a perfect point source[2]. Consulting the manual, we selected a value of 0.00029 cGy m^2/h/mCi to replace the product of Γ and f_{med}, and since the HVL of Cs rays in water is 8.2 cm^2, the linear attenuation coefficient was calculated as 0.08 [5].

We then developed an orthogonal image acquisition program to acquire the coordinate of sources from the orthogonal simulation films (see figures 1 and 2) and convert them to the patient coordinates for calculation. Dummies where used to visualize the sources and important points[2] of ICRU Report 38 were marked on the film and subsequently imported to the program.

<figure-1: Lateral simulation film showing there rectal points, a bladder point, and brachytherapy sources inside tandem and ovoid of a Fletcher-Suite-Delcalos applicator>

<figure-2: Importing the marks from the simulation films to the planning program>

The dimensions of the applicator are 8x3x3 cm. The dose calculation was set to 10 cm in each direction from the center of the applicator, encompassing an 8000 cm^3 cube. Measurements were made each 0.5 cm, constituting a total of 64000 calculations for each change in the system. The dimensions of dose grid allow for the addition of teletherapy with central block in future research.

The Lorensen and Cline's Marching Cubes algorithm was implemented using the LISP programming language. the protocol was simplified by employing a lookup table and a case index system, as suggested by John Wiseman[13], to narrow down the

256 different combinations to just 15 (see figure 3). A hash table was used to avoid recalculating values already calculated (see figure 4). Macros replaced real functions to achieve maximum performance. Wherever the precise intersection of lines and cubes was not known, linear interpolation was employed to decide on a reasonable point.

<figure 3- the 256 cases of Lorensen could be narrowed down to 15, speeding up the calculations by about 4 fold>

<figure 4- in each step of calculation, there are 8 vertices and 12 edges, but 9 wedges and 7 vertices are shared by the neighboring cubes, which have already been calculated>

The OpenGL 1.1 standard was used to render the results[14].The calculation of vertex normals was dropped and the rendering changed to wire frame to increase speed. Display lists and quadrics were employed to avoid unnecessary machine cycles. Orthographic and perspective projections were utilized to find the exact 3D configuration of isodose surfaces along with camera rotations and movements.

The final assembly was tested considering four stages of cervical carcinoma. The GTV (groos tumor volume) was considered 20.5cc for Stage IB1, 56.6cc for IB2, 63.7 for IIB, and 77.6cc for IIIB[15]. The dose for point A, ICRU bladder points and 3 rectal points were calculated and defined using the routine methods and the customized method. The routine method consisted of no spacers for IIIB, one spacer every 3 sources for IIB, one every 2 sources for IB2 and alternating spacer and source for

IB1[16]. In the customized method the physician would manipulate the source and spacer sequence and watch the results in real time to decide the best configuration on a case by case basis. Finally the percent of GTV encompassed by the 6Gy PSV was determined for each of the methods. Volume coverage calculation was done by dividing the number grid cells whose values were at or above the covering threshold over 8.

The applicator hosted 30 pellets in tandem and 10 in each ovoid, for a total sum of 50 sources. The ovoid pair was capped with a water-equivalent cap to ensure adequate protection of the vaginal vault. Each pellet is 2.5 mm in diameter and contains 40mCi of ^{137}Cs.

Results:

The source localization system achieved an accuracy of 99.6%, having maximum error of less than 0.03 cm. the dose calculation algorithm also proved accurate and fast, calculating point doses to the precision of 0.001 Gy in a fraction of second. The whole 64000 point matrix calculation, which had to be repeated once for each source, needed the dose determination formula to be evaluated 3,200,000 times in total. This was achieved in only 12 seconds, which is roughly equal to 3 million operations per second, since there are 10 operations per evaluation of formula.

Once the whole system was calculated, changing a source to spacer or changing the strength of sources or the application time could be accomplished instantly. The user could change the isosurface threshold on the fly and decide on the appropriate configuration of sources on the basis of dose to point A and other important points of interest. The timing and dose of treatment also could easily be normalized to a certain point. Isodose curves and profiles at the level of point A, bladder, and rectal points are shown in figure 5.

<figure 5 – Profile curves at the level of Point A, Bladder, and rectum>

The modified Lorenson and Cline algorithm became 25 times faster than their original implementation and with the employment of OpenGL technology the response time was reduced to zero. As a result, the changes in the threshold value are rendered in real time, and the physician is now able to instantly see the effect of change on the distribution of dose.

<figure 6 – The lateral view, showing the sources in the tandem and ovoid, and the pear-shaped 6Gy volume and its relation with the bladder point, rectal points, and point A>

<figure 7 – Anterior view of the 6Gy volume>

The difference in planning parameters is summarized in table 1. It can be shown that in most aspects, except timing, the customized method is superior to the conventional method. In rectal dose, the two approaches have the nearly same results.

The more time that is required for the customized approach (average 11.25 min, range 5-20 min) is insignificant compared to the 2-12% gain in tumor coverage and 15-33% reduction in the bladder point dose, since this could well translate into more response to therapy and less adverse effects. The present study, however, was not designed to detect such translation.

<table 1 – difference between the customized method and the conventional method in planning parameters>

Conclusion:

We have combined and modified various rather unrelated components to assemble a system that is fast and easy to use enough to encourage the radiation oncologists to more actively participate in the treatment planning process for their patients.

By investing a reasonable amount of time, the caring physician can considerably improve the accuracy of intracavitary brachytherapy. The assembled system which is proposed in this article was accurate and its results were superior to the empiric conventional method. More convenient planning by employing algorithms that have shown success in other areas of science is one way to improve and ease the work of managing malignant diseases. Real-time planning results in the individualization of the treatment, which is surely one step closer to providing the best possible care for our patients. Future work can estimate the magnitude of this impact by measuring response or the rate of adverse effects or by using radiobiologic parameters such as tumor control probability (TCP) or normal tissue complication probability (NTCP). The lower coverage percentage for stages IIB and IIIB indicates the need of adding external beam radiation therapy to the treatment protocol. The relatively high dose to bladder is because the uterus was anteverted and the bladder point was in fact closer to the applicator than point A. Refinement in technique is needed to further separate the bladder from the treatment volume.

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None of this work would be possible without the kind help of Dr Ira Kalet and his staff from the radiation oncology department of the Washington University, Seattle.

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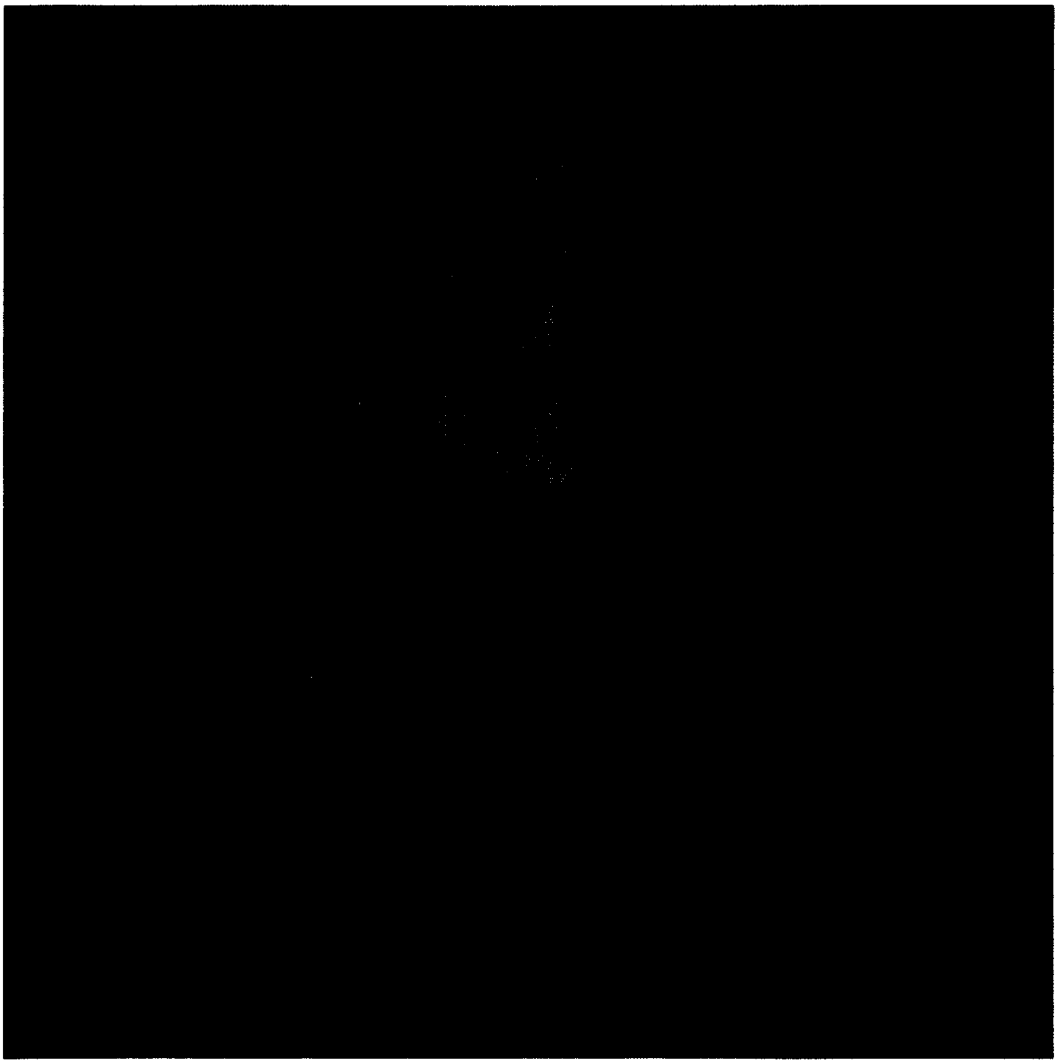
Figures:



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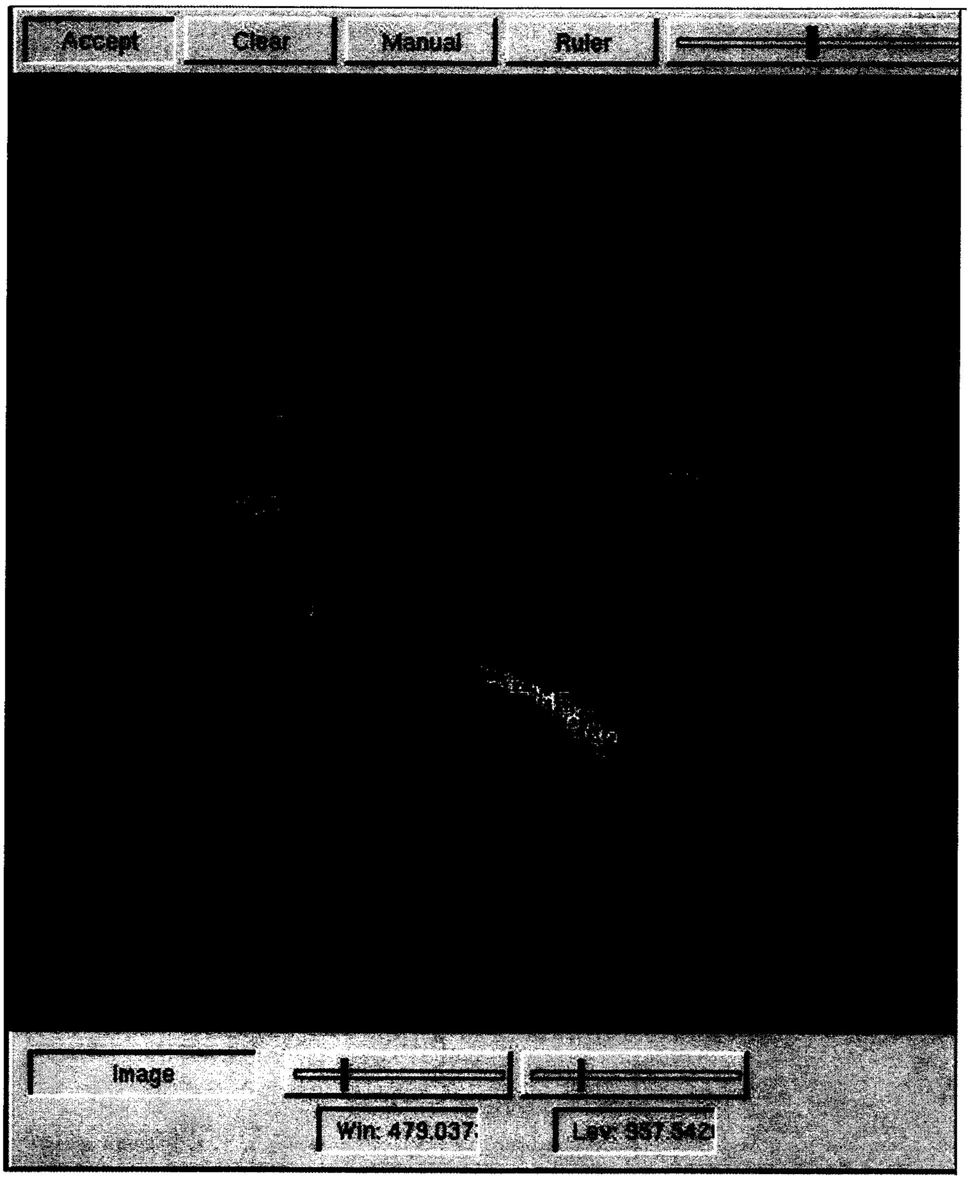

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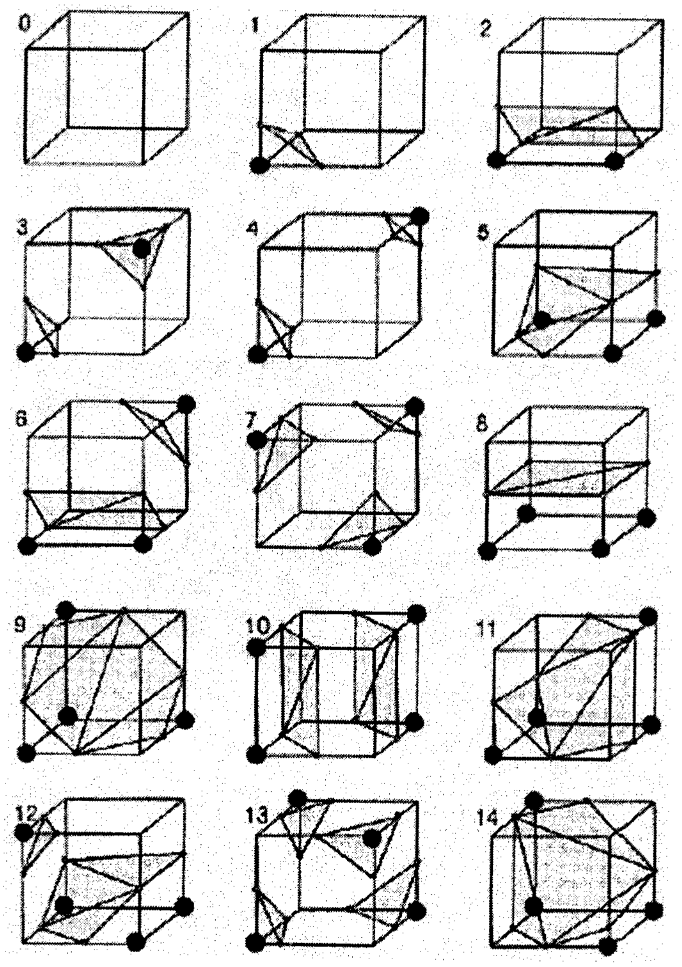

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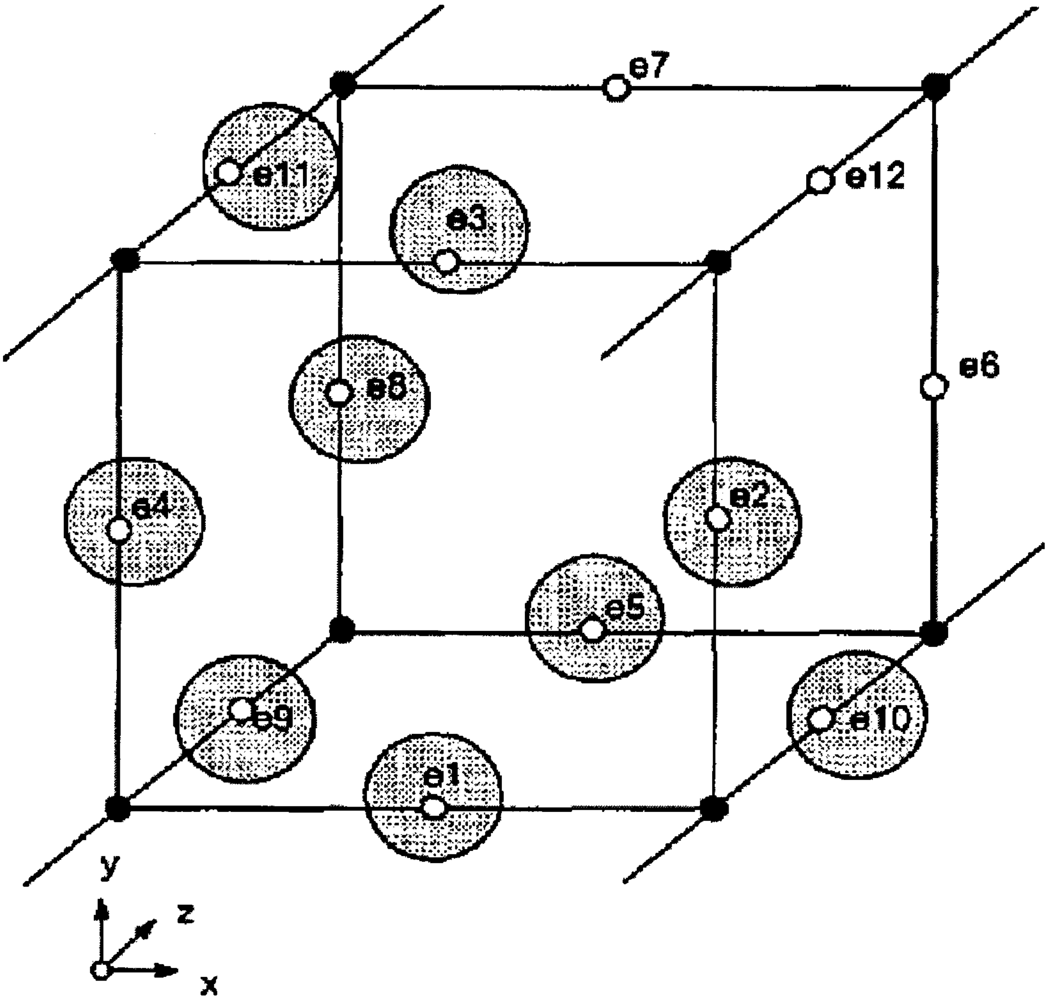

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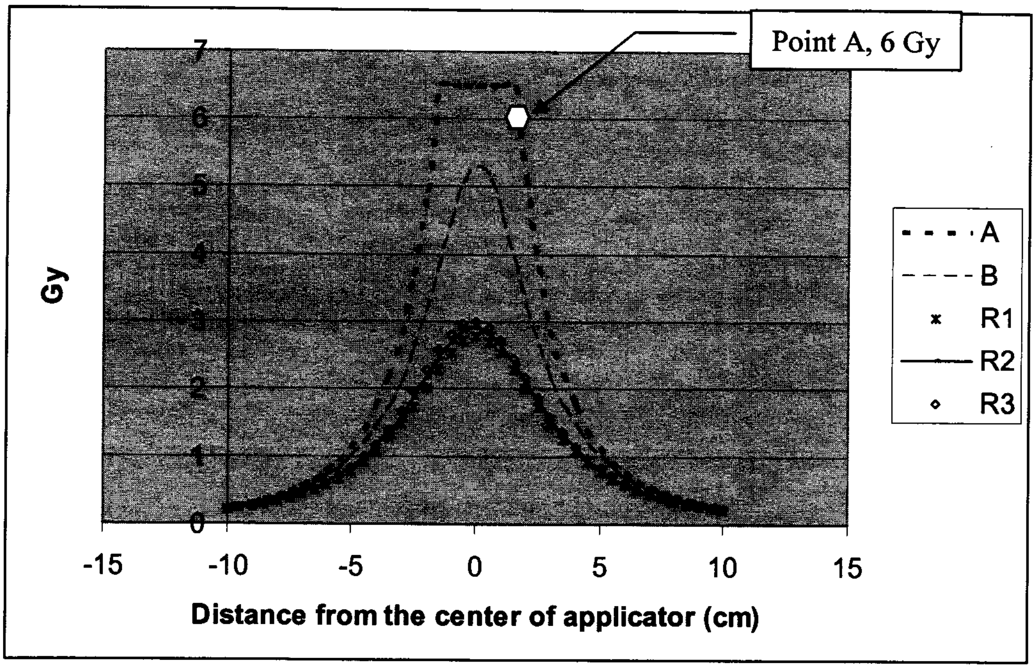

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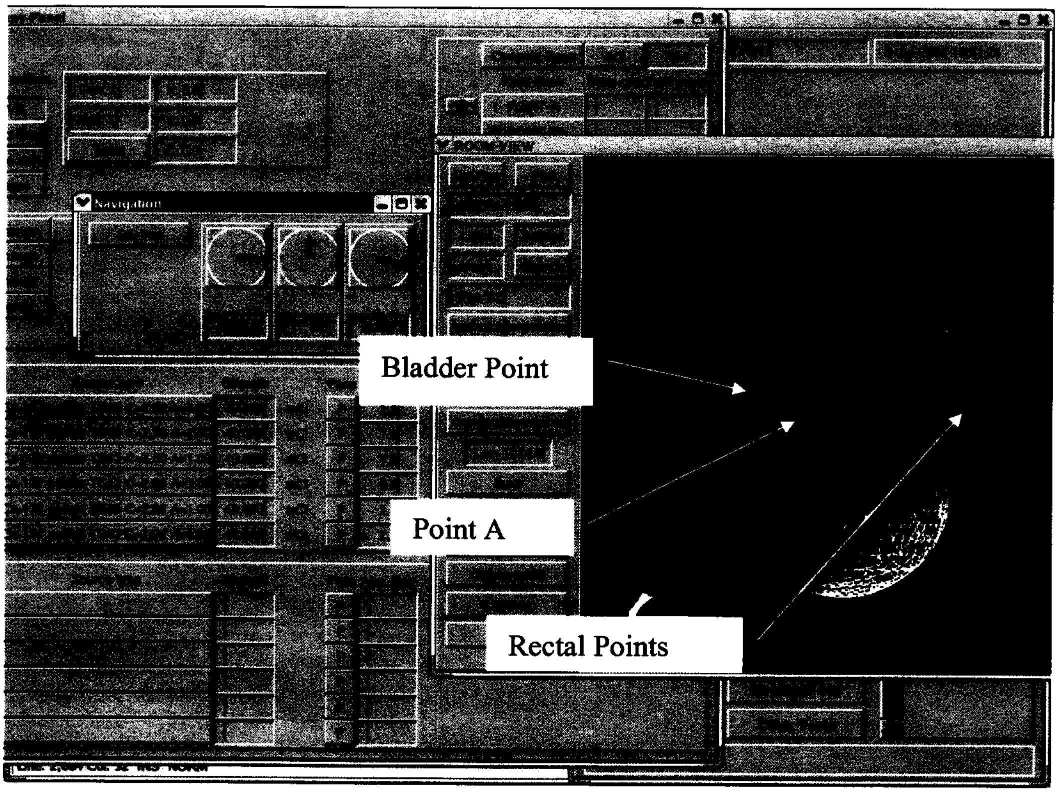

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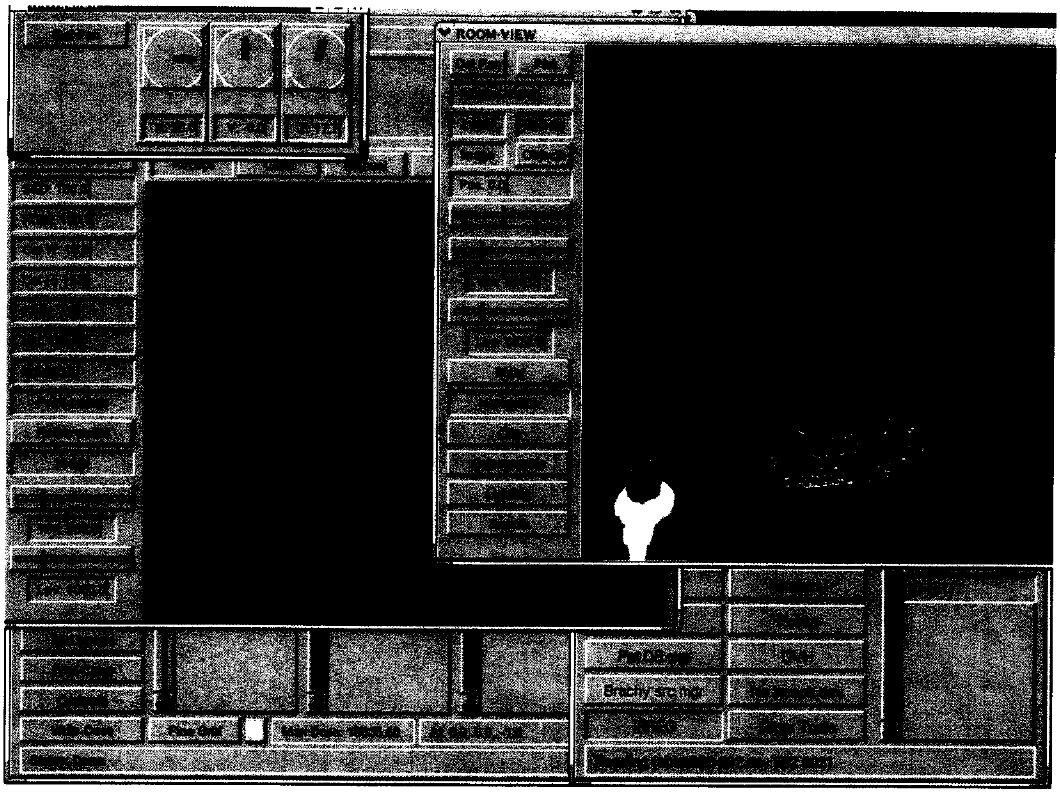

<figure 7 – Anterior view of the 6Gy volume>

Tables:

<table 1 – difference between the customized method and the conventional method in planning parameters>

Parameter	Stage IB1	IB2	IIB	IIIB
Mean GTV[1]	20.5 cc	56.6cc	63.7cc	77.6cc
PSV[2] w/EM[3]	***97%***	***82.5%***	***75%***	***67%***
PSV w/CM[4]	***99%***	***95%***	***88.2%***	***75%***
Point A w/EM	100%	100%	100%	100%
Point A w/CM	100%	100%	100%	100%
Bladder w/EM	**120%**	**123%**	**135%**	**142%**
Bladder w/CM	**112%**	**115%**	**112%**	**127%**
Low Rectal w/EM	41%	47%	52%	57%
Low Rectal w/CM	40%	45%	49%	54%
Mid Rectal w/EM	44%	49%	56%	58%
Mid Rectal w/CM	42%	47%	58%	60%
High Rectal w/EM	47%	50%	56%	63%%
High Rectal w/CM	46%	52%	54%	55%
TTP[5] w/EM	**20'**	**20'**	**20'**	**20'**
TTP w/CM	**25'**	**28'**	**32'**	**40'**

[1]GTV: gross tumor volume, [2]PSV: 6-Gy Pear Shaped Volume, [3]w/EM: using the empiric method, [4]w/CM using the customized method. [5]TTP time required for planning, in minutes.

Figure legends

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