HIPLAN – A HEAVY ION TREATMENT PLANNING SYSTEM AT HIMAC

Masahiro ENDO, Hiroko KOYAMA-ITO, Shin-ichi MINOHARA, Nobuyuki MIYAHARA, Hiromi TOMURA, Tatsuaki KANAI, Kiyomitsu KAWACHI, Hirohiko TSUIII, Kouzou MORITA

(Received 30 January 1996, accepted 2 April 1996)

Abstract: To draw the maximum advantage from accelerated heavy ions requires a treatment plan that enables us to concentrate sufficient dose to a target region and to spare surrounding critical organs. Powerful computer support is needed to implement such a plan because it is an iterative process in which we need quick changes of displayed images including three-dimensional (3D) models, and high-speed computation of 3D dose distributions. Our treatment planning system, which is called HIPLAN (Heavy Ion Plan), is constructed on modern graphical workstations running UNIX and X Window System. It implements functions required for 3D treatment planning and enables us to determine the parameters to control the irradiation system of HIMAC. In this paper we describe the software specifications, system architecture, hardware platforms and operation examples of the present version of HIPLAN, and discuss future prospects.

Key Words: Heavy ion therapy, Treatment planning, Software

INTRODUCTION

The use of heavy ions in radiation therapy may provide a therapeutic gain to deeply seated radioresistant tumors as a result of an improved dose distribution and a potential biologic advantage. To draw the maximum advantage from accelerated heavy ions requires a treatment plan that enables us to concentrate sufficient dose to a target region and to spare surrounding critical organs.

In treatment planning, a target region is first interactively input onto a three dimensional (3D) CT image. Then irradiation fields are set so as to give the prescribed dose to the target region and to spare surrounding critical organs. A dose distribution is calculated for the fields, and the calculation results are observed on the displayed images. If the dose distribution is not satisfied, the above process is repeated for different fields. In this paper we will describe our treatment planning system with which we perform the above processes at HIMAC[1].

SOFTWARE SPECIFICATION

In our treatment planning system, the following functions are available.
1. Transfer of consecutive CT images (100 slices maximum) via ethernet and conversion to the format of the treatment planning system.
2. Display of the CT images on a monitor in single or multi-slice format with image quality compatible with diagnosis. Slices are changed at a speed of more than one slice per second (depending on hardware).
3. Reformatting of coronal and sagittal sections from transverse CT images and simultaneous display thereof.
4. Interactive input of the contours of a target and surrounding critical organs onto CT images. Some contours (body outline, lung and bone)
can be automatically extracted by a threshold method.

5. Reformattting and display of the contours on the coronal and sagittal sections mentioned in process 3.

6. Generation and subsequent display of a 3D solid model of the target and organs from the contours. Surface and/or wireframe displays are available.

7. Display of the 3D model as if the viewers’ eye were placed upstream of the beam (beam’s eye view). The view point can be instantly changed so as to select the beam direction that makes the best separation of the target and critical organs. This process is called virtual simulation.

8. Definition of the beam outline as a contour of the projected target on a plane perpendicular to the beam direction, plus a margin. The patient collimator is designed so that its outline is the same as the beam outline. If a multi-leaf collimator is necessary (large field case), leaf openings are determined so that leaves are circumscribed to the beam outline. Though these processes are automatically performed, the results can be manually modified.

9. Calculation of the milling depths of compensator so that the range end of heavy ion beam is matched to the distal edge of the target. Inhomogeneities of tissues are corrected using a calibration curve relating CT number and water equivalent length per pixel.

10. Calculation of control parameters of beam delivery and shaping devices such as scatterer thickness, wobbler currents from beam specification (beam size, beam range in the body, target thickness etc.), which are obtained in the processes 8 and 9.

11. Calculation of a 3D dose distribution and its display as isodose contours on transverse CT images as well as on reformatted coronal and/or sagittal sections. Isodose surfaces can be superimposed on the 3D display of target and critical organs. Processes 8 to 11 can be performed for any beam direction, though fixed port directions (horizontal and vertical) of HIMAC limit the beam directions from which treatment can be arranged.

12. Calculation and display of dose volume histograms (DVH) for the target and critical organs.

13. Calculation and display of digitally reconstructed radiographs (DRRs) [2] form the beam direction and from the direction perpendicular to it. The contour of projected target, the outline of the patient (or multi-leaf) collimator and landmarks are superimposed on each DRR, which is used for patient positioning.

14. Numerical description of the outline of the patient collimator and thickness of the compensator and transfer thereof to a computer aided designing and machining (CAD/M) terminal, at which these data are converted to a standard format and used to fabricate the patient collimator and compensator with a numerically controlled (NC) milling machine.

15. Transfer of control parameters of beam delivery and shaping devices together with DRRs to aid positioning to a HIMAC irradiation room computer.

16. Storing of major displayed images (such as dose distributions and DRRs) for treatment round meetings. Images can be presented as hard copies or on a large screen video projector. Most of the above functions had already been implemented on the treatment planning systems at heavy ion or proton therapy facilities such as Lawrence Berkeley Laboratory or Massachusetts General Hospital when we started to prepare heavy ion therapy [3, 4, 5, 6]. However, their systems were based on the VAX/VMS System which was not compatible with modern computer technology. Therefore, we developed a new system on graphics workstations running UNIX and X Window System. During this development we added several new features such as dose calculation of non-coplanar beams, and site-specific modifications which included calculation of control parameters of beam delivery and shaping devices.

SYSTEM ARCHITECTURE AND HARDWARE

Fig. 1 illustrates system architecture that we built in order to realize the specification mentioned in the previous section. The hardware
platforms are graphics workstations (TITAN 750V and Indigo2). We first started producing treatment planning software on a TITAN 750V (Kubota Computer Inc.) and this system was used in the early clinical trials. Because TITAN 750V became obsolete due to rapid progress in computer technology, we moved to Indigo2 (Silicon Graphics Inc.). Indigo2 is roughly three times faster than TITAN 750V in calculation and rendering speed.

The operating systems (OS) of the both computers are UNIX with X Window System libraries (Xlib and X Toolkit). OSF/Motif is used as the graphical user interface (GUI) on Indigo2. 3D graphics libraries are DORE (Dynamic Object Rendering Environment) and AVS (Application Visualization System) for TITAN 750V, and GL (Graphics Library) for Indigo2. Dr.View, which was produced by Asahi Kasei Joho System, is a general purpose medical image processing software system, on which our treatment planning system named HIPLAN (Heavy Ion Plan) is constructed.

**IRRADIATION PARAMETERS AND DOSE CALCULATION**

Finely focused mono-energy beam immediately after extraction from the accelerator must be broadened in space and energy and be shaped to match a target volume before irradiating a patient. This is performed by irradiation devices consisting of wobbler magnets (a horizontal and vertical pair), a scatterer, a ring collimator, a ridge filter, a range shifter, a 4-leaf collimator, a multi-leaf collimator, a compensator and a patient collimator aligned from upstream. In our system we must determine the control parameters of these devices as one of the processes in treatment planning. Because the detailed logic of determining the irradiation parameters are too complex to fully described here, we will simply present the essence of the process.

First, a beam outline is defined as a contour of the projected target on a plane perpendicular to the beam direction, plus a margin. Beam diameter $d$ is defined as the maximum diameter of the beam outline. Water equivalent length (WEL) from upstream of the beam to proximal and distal edges of target within a body $w_l$ and $w_2$ are calculated by transforming pixel CT-numbers to WEL and integrating them along a beam path, where $w_l$ and $w_2$ are functions of coordinates $(y,z)$ shown in Fig. 2. Using these two parameters, residual range $R$, maximum thickness of target $W$ and thicknesses of compensator $T(y,z)$ are calculated as follows.

Fig. 1 System architecture of HIPLAN. Hardware platforms are TITAN 750V and Indigo2. The operating system (OS) of both computers are UNIX with X Window System libraries (Xlib and X Toolkit). OSF/Motif is used as graphical user interface (GUI) in Indigo2. 3D graphics libraries are DORE (Dynamic Object Rendering Environment) and AVS (Application Visualization System) for TITAN 750V, and GL (Graphics Library) for Indigo2. Dr.View is a general purpose medical image processing software system, on which our treatment planning system named HIPLAN (Heavy Ion Plan) is constructed.
Then irradiation parameters are calculated from \(d, R\) and \(W\). For example, the spread out Bragg peak (SOBP) width of ridge filter is determined from \(W\) and range shifter thickness is determined from \(R\). Depth dose distribution is also selected from the ridge filter and beam diameter \(d\).

Dose calculation is made using a ray-tracing algorithm immediately after determination of irradiation parameters.\[5\] \(Wp(x,y)\) is calculated as the water equivalent length to dose calculation point \(P(x,y)\) along the beam path, where \(Wp(x,y)\) includes thickness of compensator \(T(y,z0)\) (\(z0\) is the \(z\) coordinate of the dose calculation point). That is

\[
Wp(x,y) = T(y,z0) + Wp'(x,y)
\]

where \(Wp'(x,y)\) is the water equivalent length within a patient body, as shown in Fig. 3. Dose value at point \(P\) is as follows.

\[
Dp = Dr \times P(Wp-R+R0) \times S(yd)
\]

where \(Dr\) is the prescribed SOBP dose, \(P\) is the percent depth dose (100% at SOBP center), where dose means biological equivalent dose. \(R0\) is the maximum range of the beam. \(S(yd)\) is a factor between 0 and 1 that shows the penumbra at the collimator edge. \(yd\) is the length between point \(P\) to collimator edge along \(y\) direction. Function \(S(y)\) is given by the error function as follows.

\[
S(y) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{y/\sigma} e^{-t^2} dt
\]

where \(\sigma\) is a penumbra parameter.

**PHANTOM EXPERIMENT**

In order to examine the accuracy of the dose calculation, dose values at several points in a head phantom were measured to therapeutic beams and compared with calculated ones.

Dosimeters, a PTW chamber and semiconductors were inserted into a hole of 1cm diameter drilled from the left lower jaw to the left upper jaw in the phantom. Fig. 4 shows a CT image of the phantom. Treatment planning was made to irradiate a target including the dosimeters by horizontally opposed fields. In planning, the maximum physical dose was set to 1.00 Gy.

The results are shown in Table 1, and indicate that differences between calculated and measured
values were approximately 2% for field #1 which passed through only soft tissues and that differences were approximately 5% for field #2, passed through bones and teeth as well as soft tissues.

EXAMPLES OF TREATMENT PLANNING

Fig. 5 shows a target contour input interactively onto a CT image of a patient with lung cancer. Fig. 6a) shows a 3D model of the target and critical organs of the same patient as shown in Fig. 5. The target and cord are shown in surface format, while left and right lungs are shown in wireframe format. Fig. 6b) shows the same model from a slightly different view angle. This view separation of the target and cord is better than the other view. Fig. 7 shows isodose contours on the CT image. Fig. 8 shows isodose contours on the CT image and reformatted sagittal and coronal images. Fig. 9 shows a DRR with landmarks, a projected target contour and a collimator outline. This image is used for patient positioning.

Table 1. Comparison between calculated and measured dose values. CH1, CH2 and CH3 denote channels of the semiconductor detector, while PTW denotes the PTW chamber. For field #2 the value of CH3 was omitted because it was positioned at the edge of the collimator.

<table>
<thead>
<tr>
<th></th>
<th>Calculated(A)</th>
<th>Measured(B)</th>
<th>B/A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field #1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CH1</td>
<td>0.93 Gy</td>
<td>0.918 Gy</td>
<td>98.7%</td>
</tr>
<tr>
<td>CH2</td>
<td>0.98</td>
<td>1.002</td>
<td>102.2</td>
</tr>
<tr>
<td>CH3</td>
<td>0.98</td>
<td>0.986</td>
<td>100.6</td>
</tr>
<tr>
<td>PTW</td>
<td>0.85</td>
<td>0.862</td>
<td>101.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Calculated(A)</th>
<th>Measured(B)</th>
<th>B/A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field #2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CH1</td>
<td>0.94 Gy</td>
<td>0.892</td>
<td>94.6%</td>
</tr>
<tr>
<td>CH2</td>
<td>0.89</td>
<td>0.960</td>
<td>107.9</td>
</tr>
<tr>
<td>PTW</td>
<td>0.96</td>
<td>0.951</td>
<td>99.1</td>
</tr>
</tbody>
</table>

It requires from half a day to full day to complete a treatment plan in routine clinical practice. One of time consuming processes is contouring of target and critical organs. Dose calculation is also time consuming because it is an often repeated process.
Fig. 6 Virtual simulation. Perspective views of the target and critical organs, where the target (yellow) and cord (magenta) are shown in surface format and left and right lungs (brown and orange respectively) are shown in wireframe format. View angles are slightly changed between a) and b).

Fig. 7 Dose distributions (isodose contours) on a CT image. Values in the upper right corner show percent doses of the same-coloured lines, for example the red line shows 97% of maximum dose.

DISCUSSION

At the present time we are making a treatment plan using the system mentioned above, though it satisfies only basic requirements. Future developments will include the following capabilities.

1. At present we can formulate a treatment plan only with a constant range shifter thickness and fixed collimator aperture. However our irradiation devices can change range shifter thickness and collimator aperture continuously during irradiation, which enables 3D dynamic
conformal therapy. We plan to implement a function enabling us to implement such a treatment plan and to determine irradiation parameters of such therapy.

2. With the present system we can use only CT images for inputting a target contour. However the target may be delineated better with MRI or PET images. Dose calculation requires CT images, because only CT numbers can be related to water equivalent length. Therefore precise registration of CT and PET/MRI images is necessary. This technique
is called image correlation[7], which recently has been developed in the field of conventional and proton therapy. This function will be implemented in the near future.

3. We are now using a ray tracing algorithm [5] to calculate dose distributions. Except for penumbras at the collimator edge it does not take effects of multiple scattering into account. Recently a group of authors has proposed a method that takes multiple scattering into account[8]. They showed their method might be useful to dose calculations in highly heterogeneous regions that contain tissue-air or tissue-bone interfaces. We are now developing our own algorithm that enables a precise estimation of multiple scattering not only in the patient but also in the beam shaping devices.

4. It is a tedious task to input contours of critical organs onto consecutive CT images. At present only the contours of body, lung and bone can be extracted automatically by the threshold method. We will implement more sophisticated algorithms for automated extraction of critical organ contours, which will be effective for kidney, liver, rectum, bladder etc..

ACKNOWLEDGEMENTS: The authors thank Hirohumi Nishimura and Hiroyoshi Oka of Asahi Kasei Joho (Information) System Co. Ltd. for their software work.

REFERENCES