Radiat Environ Biophys (1992) 31:251–256

**Radiation and Environmental Biophysics**



# Dose calculation and optimization for 3D conformal voxel scanning*

**S. Scheib and E. Pedroni**

Paul Scherrer Institute, Department of Radiation Medicine, CH-5232 Villigen PSI, Switzerland

Received December 16, 1991 / Accepted in revised form February 17, 1992

**Summary.** A new dose application method, the voxel scanning, is described which permits three-dimensional irradiation of deep seated tumors.

## Introduction

At the Paul Scherrer Institute (PSI) in Villigen, Switzerland, a proton pencil beam with variable energy (100–200 MeV) corresponding to a range of 16 to 26 cm in tissue will be available in April 1992. A new dose application method, the voxel scanning is now under development. This fully computerized technique permits the three-dimensional, irradiation conformal to arbitrary shaped, deep seated tumors without individual hardware for patients. To allow multiple field irradiations the use of a small, compact gantry is planned. The practical feasibility of this voxel scanning technique was demonstrated during our first test beam period at the end of 1989 [1, 2].

## Experimental data and physical dose model

Measurements and calculations of the spatial dose distribution of the proton pencil beam are the basis for our three-dimensional treatment planning and dose calculations. We have analyzed the experimental data taken during our test beam period and developed a simple physical dose model, which describes the spatial dose distribution of a single pencil beam. The measured dose distribution can be described as a two-dimensional Gaussian distribution of varying amplitude and having a different width sigma at each depth. The integration of this dose distribution for each depth along the two lateral axes yields the total dose deposited at this depth, the well known Bragg curve.

* Invited paper given on the fourth workshop on "Heavy Charged Particles in Biology and Medicine" GSI, Darmstadt, FRG, September 23–25, 1991

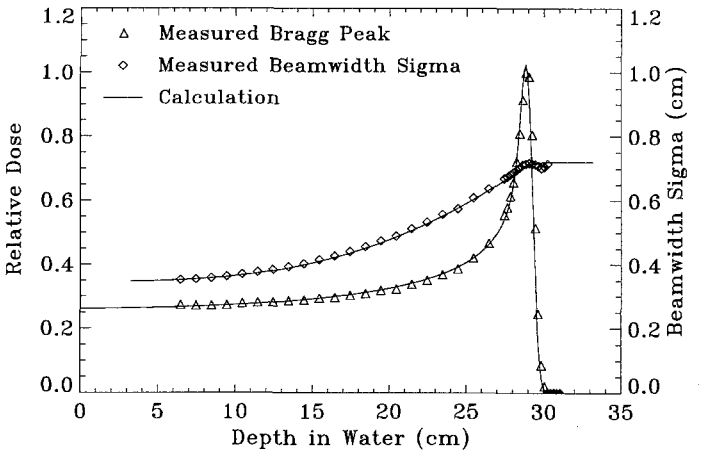


**Fig. 1.** Measured and calculated Bragg peak and beam width sigma

To calculate the Bragg curves for different incident proton energies we generated a look-up table containing the stopping power for incident protons with a given energy in water. The effect of multiple scattering within the absorber was calculated with a Gaussian distribution of the scattering angle according to Highlands formula [3]. In the case of a homogeneous medium, the overall effect of the multiple scattering on the beam shape can be integrated analytically along the depth [4]. This formalism was already used in the treatment planning for the pion therapy at PSI [5]. A detailed presentation of a similar formalism is given by Farley and Carli [6]. To take into account the beam attenuation by elastic and inelastic scattering in our physical dose model, we included the total reaction cross section on $^{16}O$ [7, 8, 9] and an effective total elastic proton-proton cross section [10]. Protons undergoing nuclear reactions within the absorber material are removed from the primary beam and do not contribute to the deposited dose in our model. No tracking of the scattered protons and the reaction products is done. In order to describe the effect of range straggling and the momentum band of the protons, we used a Gaussian distribution of the primary energy with a constant width.

To fit our experimental data we chose a primary proton energy of 214.3 MeV, a momentum band of 0.4% and a value for the constant $E_s$ in Highlands formula of 18 MeV. The initial phase space of the beam has been determined by measurements in air. In Fig. 1 the experimental data taken at PSI are compared to our physical model calculations.

## 3D dose calculation and optimization

Assuming a typical spot separation of 0.5 cm and a tumor volume of about 1 l, up to 10000 beam spots have to be distributed inside the patients body. The location of each beam spot is calculated with the help of calibrated CT images. Inhomogeneities are taken into account by calculating the integral density only on the axis of each individual pencil beam. The stacking of the individual Bragg peaks in depth is achieved at PSI by inserting 0.5 cm water equivalent

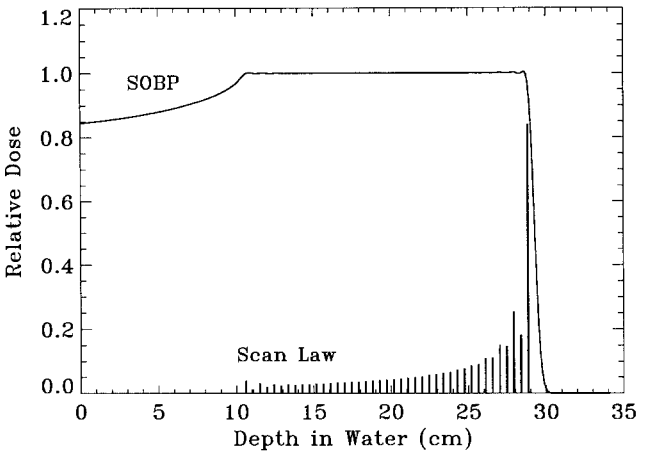


**Fig. 2.** Calculated Spread Out Bragg Peak (SOBP) and "scan law" for 40 range shifter plates

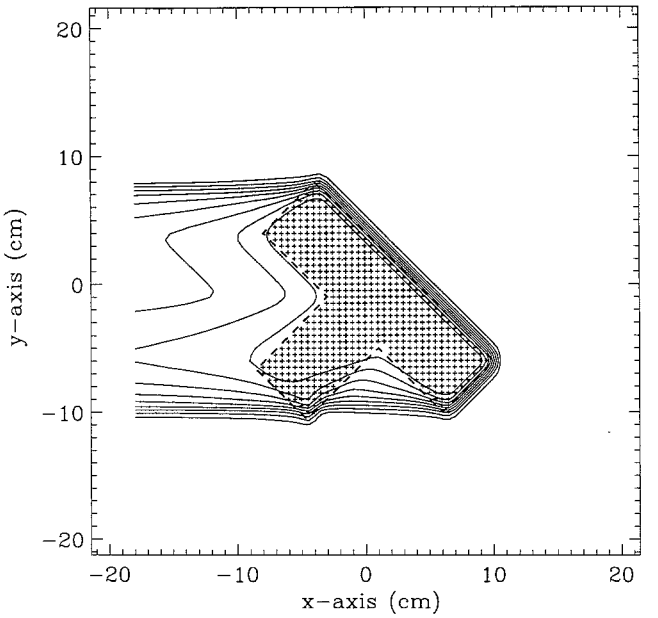


**Fig. 3.** First calculation of the dose distribution without optimization for a geometrical target volume (*dashed line*) with a proton range of 29 cm. The isodose lines correspond to 10, 20, 30, 40, 50, 60, 70, 80 and 90% of the maximum. The Bragg peaks are marked with crosses

range shifter plates into the beam path. This causes a "pull back" of the Bragg peak inside the patient. To calculate the deposited dose inside the patient, the integral dose and beam width are taken from look-up tables of the undisturbed beam in the water phantom at the corresponding water equivalent depth. The influence of the spatial distribution of the inhomogeneities perpendicular to

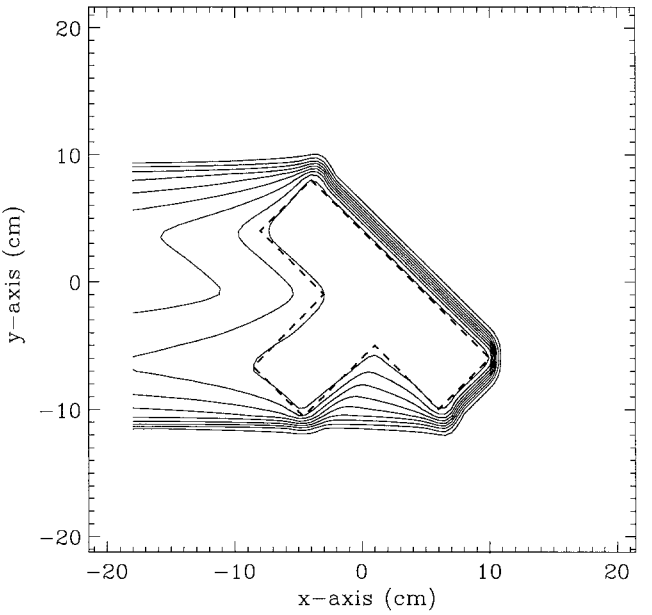


**Fig. 4.** Same as Fig. 3, but with optimization of the beam spot intensities

the beam axis on the beam width is not yet considered in our dose calculation. The effect of an air gap between the range shifter and the patient on the beam width is included. The dose applied of each beam spot can be assigned individually. The flexibility of the voxel scanning method permits the construction of a homogeneous, three-dimensional, arbitrary shaped dose distribution within the target volume and a steep lateral and distal dose fall-off outside.

In a first test we tried to reach the three-dimensional dose conformation by assigning the dose of each spot according to a general "scan law" shown in Fig. 2. This "scan law" is the result of the one-dimensional optimization of 40 shifted Bragg peaks to get a homogeneous Spread Out Bragg Peak (SOBP). As shown in Fig. 3 the dose conformation is only approximate if we switch on all spots inside the target contour. This result demonstrates the importance of dose optimization procedures to get the best three-dimensional dose conformation to the target volume.

In a second procedure we used an iterative $\chi^2$ minimisation procedure to optimize the dose distribution. This method is similar to the one used in the treatment planning system developed for pion therapy at PSI [11]. A precalculated "desired" dose distribution is compared with the one calculated using the general "scan law". Then a $\chi^2$ function is defined which can be minimized in an iterative procedure, by varying the intensity of each spot. The result of this optimization is shown in Fig. 4. The improvement in the conformation of the 90% isodose line with the target contour is obvious. The resultant dose distribution of three individually optimized fields is shown in Fig. 5. This result demonstrates the advantage of multiple field irradiations, which will be possible with the use of the proposed compact gantry at PSI. For a typical volume of about 1 l and a dose-grid spacing of 0.5 cm this optimization takes for each

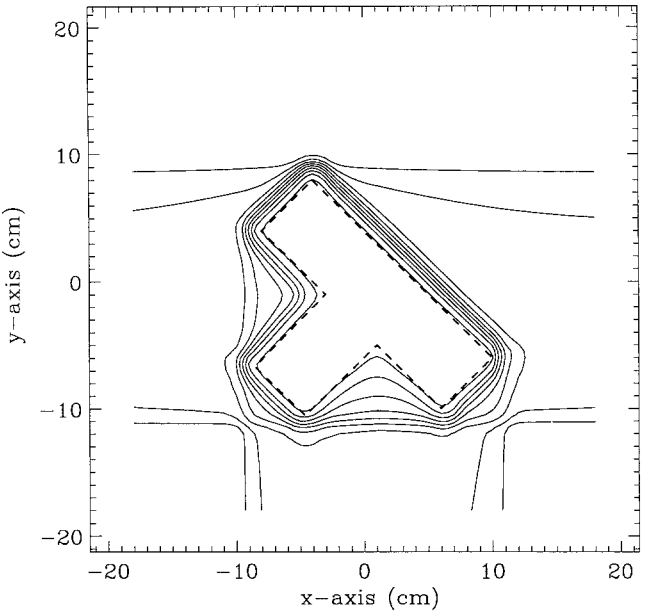


**Fig. 5.** Superposition of three individual optimized fields as an example of multiple field irradiations on the gantry

field 150 s on a vector processor (VAX 9000-410, Digital Equipment Corp., Maynard, MA).

## Outlook

Our future goals are to introduce some weighting of the $\chi^2$ function to improve the lateral and distal dose fall-off outside the target contour. This should lead to a significant improvement of the edge definition of the dose distribution. We will also include the effects of collimators and compensator boluses, which could be advantageous in some special applications. Such refined three-dimensional dose calculations, including also the spatial distribution of the inhomogeneities perpendicular to the beam axis, should be implemented without increasing the computing time to unacceptable values. Then the option of multiple field optimization should be implemented, which will deal completely with the full flexibility offered by the voxel scanning method. For the therapeutic application of heavier charged particles like helium and carbon ions, the biological effects of the pencil beam along its path have to be evaluated. This macroscopic view, dealing with a biological depth dose curve, allows the calculation of homogeneous, biological dose distributions for a given dose and biological system. This first order approach could be included into the treatment planning program, if experimental data is available. Finally, errors in the dose application system have to be included into the dose calculations. This will allow a detailed study of the error propagation and help defining design values for the beam delivery system to guarantee the needed precision of the dose application.

## References


1. Pedroni E, Bacher R, Blattmann H, Boehringer T, Coray A, Egger E, Phillips M, Scheib S (1989) The 200 MeV Proton Therapie Project at PSI: A Status Report. Proceedings of the International Heavy Particle Therapy Workshop, PSI, Sept. 18–20, 1989, pp 1–8
2. Bacher R, Blattmann H, Boehringer T, Coray A, Egger E, Pedroni E, Phillips M, Scheib S (1989) Development and first results of discrete dynamic spot scanning with protons. Proceedings of the International Heavy Particle Therapy Workshop, PSI, Sept. 18–20, 1989, pp 9–12
3. Highland VL (1975) Some practical remarks on multiple scattering. Nucl Instrum Methods 129:497
   Highland VL (1979) Erratum to some practical remarks on multiple scattering. Nucl Instrum Methods 161:171
4. Øverås H (1960) On small angle multiple scattering in confined bodies. CERN Yellow Report 60-18
5. Pedroni E (1979) Bern04 – Pion irradiation of a pancreas tumor. An example of therapy. Planning for the SIN pion applicator, TM-65-02, SIN 1979
6. Farley FJM, Carli C (1990) EULIMA Beam Delivery, Proceedings of the 2nd European Particle Conference, Nice, June 12–16, 1990, S 73
7. Janni JF (1982) Proton range energy tables, 1 keV – 10 GeV, At Data Nucl Data Tables 27:147
8. Renberg PU, Measday DF, Pepin M, Schwaller P, Favier B, Richard-Serre C (1972) Reaction cross sections for protons in the energy range 220–570 MeV. Nucl Phys A 183:81
9. Carlson RF, Cox AJ, Nimmo JR, Davison NE, Elbakr SA, Horton JL, Houdayer A, Sourkes AM, Oers WTH van, Margaziotis DJ (1975) Proton total reaction cross sections for the doubly magic nuclei $^{16}O$, $^{40}Ca$, $^{208}Pb$ in the energy range 20–50 MeV. Phys Rev C12:1167
10. Measday DF, Richard-Serre C (1969) Loss of protons by nuclear interactions in various materials. CERN Yellow Report 61-17, 1969
11. Pedroni E (1981) Therapy planning system for the SIN-pion therapy facility. In: Burger G, Breit A, Broerse JJ (eds) Treatment planning for external beam therapy with neutrons. Urban & Schwarzenberg, München, pp 60–69