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ORIGINAL PAPER

Influence of the energy spectrum and spatial spread of proton beams used in eye tumor treatment on the depth-dose characteristics

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Abstract. The influence of the energy spectrum and the spatial spread of a therapeutic proton beam impinging on an irradiated medium (called the entrance beam) on the depth-dose characteristics in water, in the proton energy range of 50÷70 MeV was studied. It turns out that full width at half maximum (FWHM) of the Bragg peak increases almost linearly with increasing proton energy. It ranges from 1.53 mm for 50 MeV to 2.59 mm for 70 MeV, for monoenergetic protons. Moreover, the significant influence of the energy spread of the entrance proton beam on the intensity and FWHM of the Bragg peak is visible. FWHM of the Bragg peak of 60 MeV protons is equal to 2.03, 3.37 and 5.86 mm for a monoenergetic beam and beams with an energy spread of 0.5 and 1 MeV SD (standard deviation), respectively. The intensity of the Bragg peak of a 60 MeV proton beam with an energy spread of 1 MeV SD is approximately 25% less than that for a monoenergetic beam. Moreover, the Bragg peak shifts to smaller depths as the energy spread of the entrance beam increases. The shift of the peak is about 0.2÷0.3 mm for a beam with an energy spread of 0.5 MeV SD and between 0.4÷0.5 mm for an energy spread of 1 MeV SD, compared with a monoenergetic beam in the energy range from 50 to 60 MeV. However, the spatial spread of the entrance proton beam does not affect significantly the depth-dose characteristic.

Key words: Bragg peak • proton therapy • Monte Carlo calculations

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Introduction

The newest face of radiotherapy is proton therapy. Protons exhibit little scattering when they penetrate matter and give the highest energy deposition (called the Bragg peak) near the end of their range. Such characteristics allow the shape of the dose distribution inside the patient's body to be very precisely controlled [4, 7]. Protons with an energy of about 60 MeV are applied for the treatment of eye tumors [1, 2]. In this case, the optimization of the beam parameters is of the highest importance because of the closeness of the retina. The influence of the energy spectrum and the spatial spread of the therapeutic proton beam on the depth-dose characteristics in water, in the proton energy range of 50÷70 MeV was studied. The depth-dose characteristics were determined in water – a medium recommended by the dosimetry protocols [5] for dosimetry measurements and calculations because water has the mass collision stopping powers and linear scattering powers approximately equal to those of biological tissues. The investigations were based on Monte Carlo calculations. The calculations were realized by computer simulations carried out with the use of the GEANT4 Monte Carlo simulation tool kit [3, 6] worked out by European Organization for Nuclear Research (CERN). The spatial and energy spread of the proton beams considered had a Gaussian distribution with various FWHM values. Our

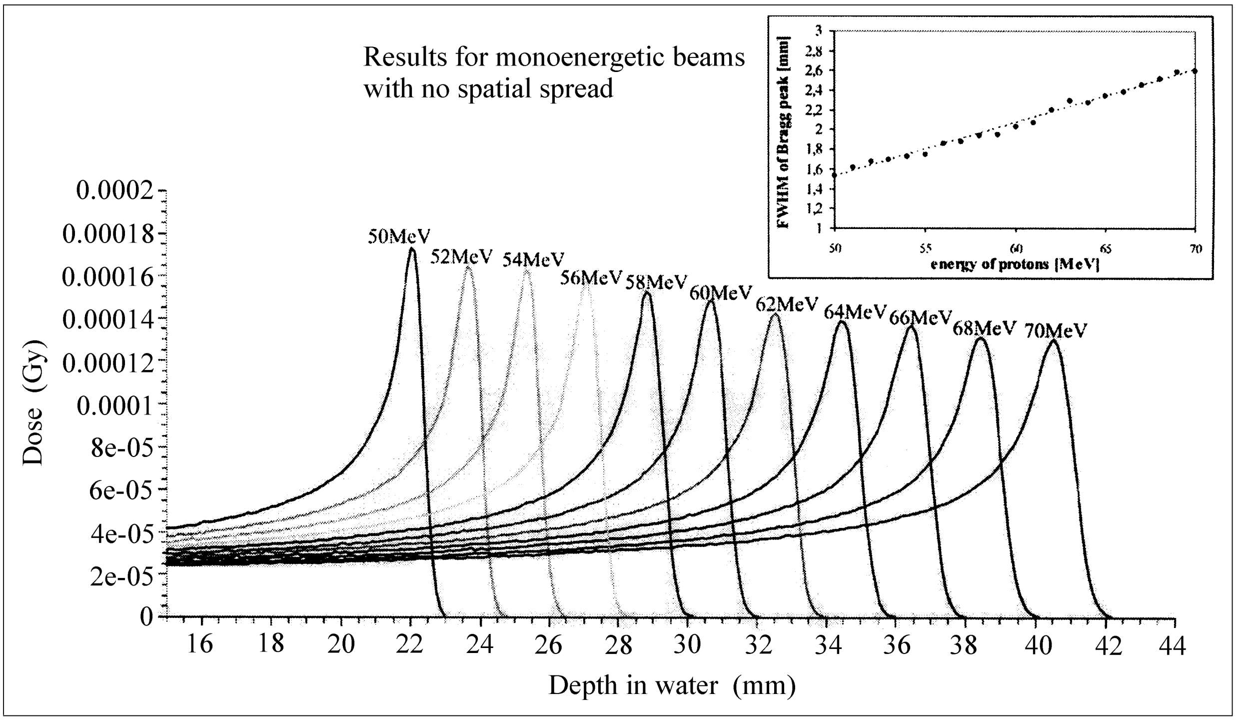

Fig. 1. Depth-dose characteristics of monoenergetic proton beams with no spatial spread; the dependence of energy of these beams on FWHM of the Bragg peak in the inset. Dose in Gy were determined in the bin volume for 10 000 protons.

calculations were carried out using computers in the Department of Nuclear Physics and Its Applications of the Silesian University (Katowice, Poland), under the Linux operating system.

Methods

The depth-dose characteristics were calculated in a water phantom model in the shape of a sphere of diameter 5 cm. The doses were calculated in logic detectors often called the bins. In our calculations the bins were 0.1 mm thick cylinders with a radius of 5 mm. 500 bins were defined along the central-axis of the beam, to cover all the depth range up to 5 cm. The central-axis of the beam was in line with the symmetry axis of the sphere. Each depth-dose characteristic was obtained for an entrance beam (i.e. the beam coming to the irradiated medium) consisting of 10 000 protons. Energies of protons ranged from 50 to 70 MeV with a step of 2 MeV. Monoenergetic protons and two beams with SD of 0.5 and 1 MeV were simulated to check the influence of the energy spread on the depth-dose characteristics. The energy spread does not exceed 2% of the mean energy of the beam which is a norm for clinical proton beams. A beam without a spatial spread and with an energy spread of 2.5 mm SD was considered. The calculation program was based on the GEANT4 libraries (version 4.7.1). We decided to use the GEANT4 simulation tool kit because it is often applied to simulate beams in hadron therapy (for example [8, 9]). In addition, GEANT4 consists of a broad collection of C++ class libraries which the users can use to build their own simulation program, i.e. any part of the source code can be overwritten. As a result of this, the users have unrestricted control over the calculation.

Results

The first stage of the presented investigations was the determination of the influence of an energy of a monoenergetic entrance proton beam with no spatial spread on the depth-dose characteristics (Fig. 1). It turns out that FWHM of the Bragg peak increases almost linearly with increasing proton energy. It ranges from 1.53 mm for 50 MeV to 2.59 mm for 70 MeV. Moreover, the intensity of the Bragg peak decreases for higher energies if the number of entrance protons is constant.

The main part of the work was a check of the relation between the energy spread of the entrance proton beams with the chosen energies close to 60 MeV and intensity and the width of the Bragg peak (Fig. 2). Additionally, the effect of the energy spread on the depth of the Bragg peak maximum was determined. The significant influence of the energy spread of the entrance beam on the intensity and FWHM of the Bragg peak is visible in all the considered energy range (Fig. 2). FWHM of the Bragg peak of the 60 MeV protons is equal to 2.032, 3.366 and 5.861 mm for a monoenergetic beam and beams with an energy spread of 0.5 and 1 MeV SD, respectively. The intensity of the Bragg peak of a 60 MeV proton beam with an energy spread of 1 MeV SD is approximately 25% less than that for a monoenergetic beam. Moreover, the Bragg peak shifts to smaller depths as the energy spread increases. In the case of a beam with an energy spread of 0.5 MeV SD, the shift of the peak is about 0.2÷0.3 mm compared with a monoenergetic beam in the energy range from 50 to 60 MeV. The shift of the Bragg peak increases with increasing energy spread and is between 0.4÷0.5 mm relative to monoenergetic protons for an energy spread of 1 MeV SD, for the considered energy range.

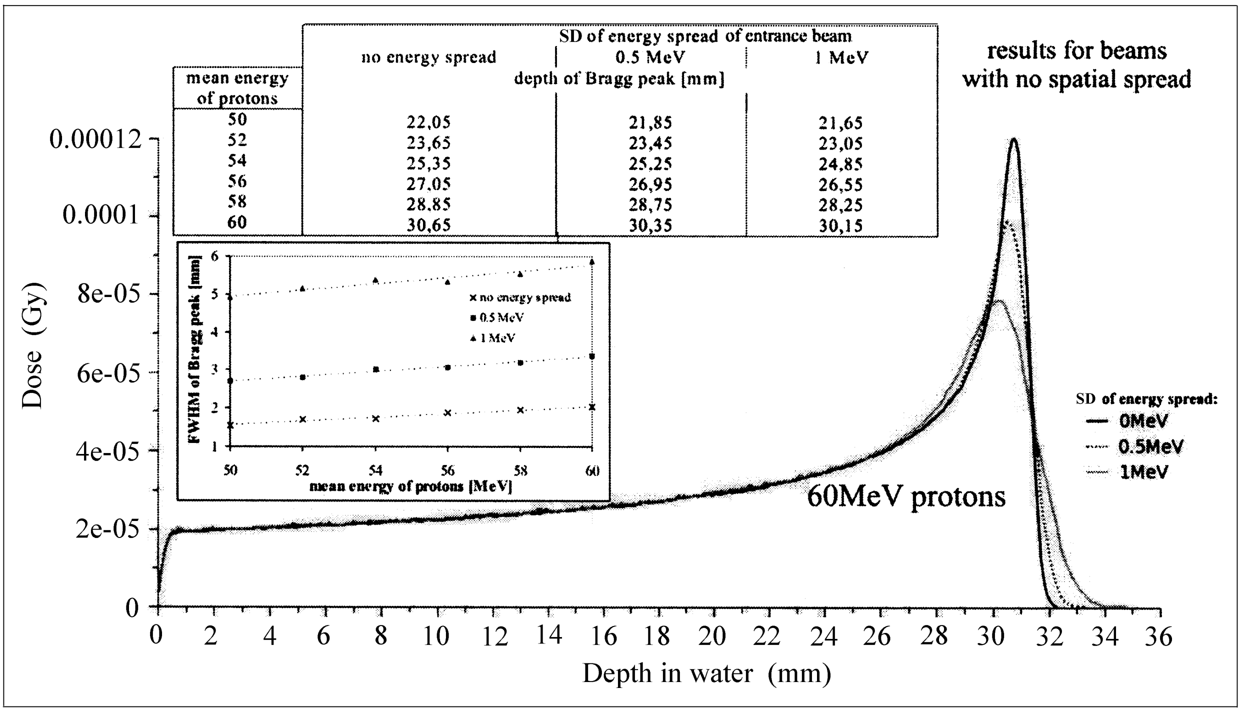

Fig. 2. Influence of the energy spread of the entrance beam on the depth-dose characteristics of 60 MeV protons; depth and FWHM of Bragg peak vs. mean energy of protons in the insets. Doses are determined as in Fig. 1.

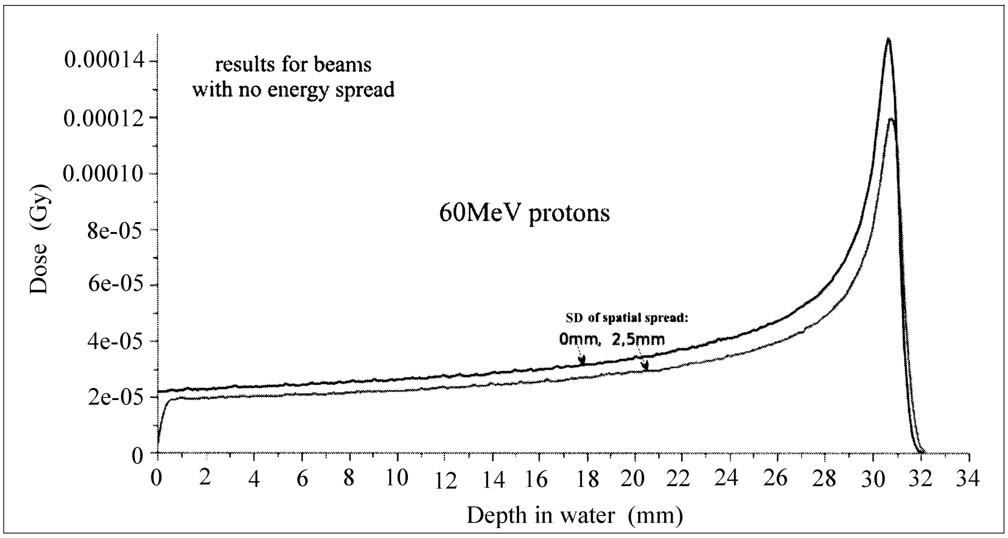

Fig. 3. Effect of spatial spread on 60 MeV proton depth-dose characteristics. Doses are determined as in Fig. 1.

The depth-dose characteristic of a 60 MeV proton beam with no spatial spread was compared with that of a beam with a spatial spread of 2.5 mm SD (Fig. 3). A comparison was performed for monoenergetic beams. It turns out that the width of the Bragg peaks is almost unaffected by the spatial spread of the proton beams considered. However, a change in intensity of the Bragg peaks was observed. It is caused by the fact that a part of the broadened beam is beyond the bin volumes. A significant shift of the Bragg peak for the broadened beam also was not observed.

Discussion and conclusions

The results obtained can be useful for clinical proton beams. The investigations presented have shown that the mean energy and the energy spread of the entrance proton beam strongly affect the depth-dose characteristics. The intensity and width of the Bragg peak as well as the depth of maximum dose depend on the mean energy and the energy spread of the entrance proton beam. Therefore, it is of highest importance to keep a constant energy spectrum of the clinical beam during irradiation. Moreover, a proton energy spectrum used in a treatment planning system ought not to differ from that of the real beam. However, the spatial spread of the entrance proton beam does not influence significantly the depth-dose characteristics.

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