

Carbon Ion Radiotherapy - - Advantages, Technical Aspects and Perspectives

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Abstract. Carbon ion radiotherapy is a groundbreaking method of treatment radioresistant tumors situated close to critical organs. The article presents the physical basis of carbon ion therapy, methods of generation and acceleration of heavy ions, systems of forming and exact positioning of the therapeutic beam. Intensity modulated particle therapy and raster scanning technique allow optimum compatibility between the irradiated volume and target volume. By dint of such methods minimum exposure of critical structures is possible. An important aspect of the treatment process is the monitoring of patient's position during the irradiation. It is possible by means of the modern imaging techniques such as PET-CT. Increase of the availability of heavy ion therapy and its development are big challenges for the physicists of the most prestigious research centers in the world.

Keywords: teleradiotherapy, carbon ion therapy, IMPT, raster scanning

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INTRODUCTION

The main advantage of carbon ions compared to conventional beams such as X-rays, gamma rays, high energy photons, electrons is different depth dose distribution. The Bragg maximum at the end of the particle range allows the application of higher dose of radiation to the tumor and protect normal tissues.

PHYSICAL BASIS OF HADRON THERAPY

Heavy ions, passing through the irradiated tissue, lose energy during multiple acts of ionization and slow down. This process is described by Bethe-Bloch formula from 1930. Ions, which penetrate the matter with high speed, leave a small portion of their energy in one interaction. Consequently, the radiation dose deposited at the beginning of path is relatively low. If the ions penetrate deeper, they will move slower and lose more energy to processes of ionization. Transferred dose reaches the highest value - Bragg maximum at the end of ions path. Although the ions have a finite range, the dose tail is observed behind the Bragg peak. Its source is the ionization processes caused by fragments of nuclear matter and neutrons, which were created as a result of carbon ions collisions with atomic nuclei of medium. Carbon ions are characterized by high energy transfer at the end of

distance traveled in a material medium, which is extremely desirable in teleradiotherapy. In contrast to photon radiation, for which maximum dose is a few centimeters below the skin surface and decreases exponentially with increasing depth, heavy ions provide the highest radiation dose in the Bragg peak region (Fig. 1). It is possible to give ions an appropriate initial energy, so that maximum energy transfer takes place precisely in the area of the tumor, and damage to adjacent healthy tissues are minimal.

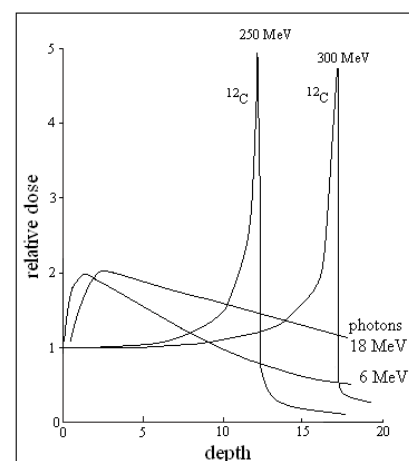


FIGURE 1. Dose distribution for ^{12}C ions and photons [1].

Carbon ions are particles with greater mass and higher charge than protons so they have sharper Bragg peak, higher linear energy transfer (LET) and thus higher relative biological effectiveness (RBE). The RBE reaches the maximum in the target volume but it is sufficiently low in the plateau before the Bragg peak.

INDICATIONS FOR CARBON ION THERAPY

Carbon ions, due to the high ionization density in the Bragg peak region, cause multiple DNA damages, even in the most radioresistant pathological cells. Therefore patients with radioresistant tumors situated in the vicinity of sensitive organs are primarily referred to the carbon ion therapy. This type of therapy is used to treat cancers of head, neck, bone, prostate, uterus, rectum, liver and lung [2]. The scope of applicability of the carbon ion therapy is still increasing.

TECHNICAL ASPECTS CARBON ION THERAPY

Compact sources, based on the effect of Electron Cyclotron Resonance (ECR), are frequently used to obtain ion beams. Furthermore scientists aim at the development of LDIA technique (laser-driven ion acceleration), which uses laser with high power (50 or 100 TW), variable phase and short pulses (20 fs) as the injector of synchrotron [3]. Afterward carbon ions are accelerated by cyclotron or synchrotron, so that their kinetic energies ranged between 80 and 430 MeV/u, which corresponds to the depth of body penetration between 2 and 30 cm. Heavy ion beam is aimed at target by a gantry, which rotates around the patient and allows the irradiation of planning target volume from different directions with high accuracy. Maximum deviation is 0.5 mm [4]. Due to the high cost of gantry construction more common is to use horizontal fixed beam treatment rooms. The Bragg peak of a monoenergetic ion beam is too narrow to be used in therapy. It must be extended to cover the tumor volume of different size and shape. Superposition of Bragg peaks is called the SOB region (Spread-Out Bragg Peak). In the earlier technical solutions a therapeutic beam was formed by passive system, based on such elements as range modulators, compensators and wedges. Nowadays the following modern irradiation techniques are used: intensity-modulated particle radiotherapy (IMPT) and raster scanning. Intensity-controlled raster scan allows a three-dimensional irradiation of the subdivided into voxels target volume. Each of the tumor spatial elements is irradiated separately by ions of a appropriate energy,

depending on the depth of the layer. Deflection of the ion beam is performed using variable magnetic fields produced by electromagnets. The beam is focused onto a specific volume element until the desired dose is reached. As a result the dose is delivered to the tumor with a millimeter precision. During the irradiation patient is immobilized and his position is monitored. The range and location of the carbon ion beam can be tracked inside the patient in real time by dint of positron emission tomography (PET). Positron emitters such as ^{10}C , ^{11}C and ^{15}O are created as a result of carbon ions collision with atoms of the tissue [5]. During the cancer treatment process on average patient receives 13 fractions of radiation spread over three weeks [2].

PERSPECTIVES

An extremely important aspect of radiation therapy is the problem of moving targets in the thorax and the abdominal region. Known techniques, such as gating (synchronization of irradiation and breathing) and multi-painting (repeated irradiation) are still imperfect [6]. Therefore the development of the respiratory gated scanning method is a challenge for physicist from research centers worldwide.

CONCLUSION

Carbon ion therapy opens new perspectives in the struggle against cancer because of inverse depth dose profile (maximum dose at the end of the range), large linear energy transfer and radiobiological effectiveness in the region of Bragg peak, reduction in treatment time and maximum protection of normal tissues.

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