Beam delivery systems in hadron therapy for cancer treatment

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Abstract: Hadron radiotherapy is a cutting-edge cancer treatment method. Proton and carbon ion beams are frequently used in modern therapeutic centers. The Bragg peak at the end of the particle range delivers a higher radiation dose to tumors situated close to critical organs. However, the accuracy of the dose deposition in the tumor volume depends on the irradiation method. The present paper presents a comparison between two totally different beam delivery systems: a passive beam shaping technique, and active scanning. The first system uses a number of passive elements to form a broad beam covering the planned target volume; while, in the case of a fully active system, a narrow pencil beam irradiates small, spatial tumor elements successively. Raster scanning enables optimum compatibility between the irradiated volume and the target volume.

1. Introduction

Hadron therapy is getting international recognition in modern medicine. Both protons and carbon ions are successfully used for cancer therapy. Their unique physical and radiobiological properties enable an effective, highly conformal treatment by precisely delivering the prescribed dose to deep-seated tumors and sparing the surrounding healthy tissues. Therefore, heavy charged particle therapy is a groundbreaking method of treatment tumors situated close to critical organs.

The main advantage of protons and carbon ions compared to conventional beams is different depth of dose distribution. In case of X-rays, after a short build-up region, the energy deposition of gamma rays and electrons decreases with increasing depth in tissue. In contrast, for protons and ions maximum energy transfer occurs at the end of the distance travelled in a material medium, which is extremely desirable in teletherapy. The pronounced maximum, called Bragg peak, can be positioned within the target by changing the initial energy of the particles. It is worth noting that carbon ions, as particles with greater mass and higher charge, have sharper Bragg peak, higher linear energy transfer (LET) and thus higher relative biological effectiveness (RBE) than protons (Kubiak, 2013). Carbon ions are more efficient in

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the fight against hypoxic tumors, which are radioresistant (Dosanjh et al., 2007). However, to fully exploit the advantages of Hadron therapy, an optimal irradiation system must be chosen.

2. Comparison of beam delivery systems

Effective delivery of the prescribed therapeutic dose to the planned target volume is performed, depending on the therapy centre, in two different ways. In spite of many disadvantages, the old passive system, in which a therapeutic beam is formed by such elements as range modulators, compensators and wedges, is still very popular. However, an increasing number of particle therapy facilities use modern active irradiation techniques such as raster scanning and intensity-modulated particle radiotherapy (IMPT) (Kubiak, 2013). It is worth looking carefully at both systems and characterizing them.

3. Passive system

The passive beam forming system contains many elements, whose role is to extend the narrow monoenergetic Bragg peak to cover the tumor volume of different size and shape (Fig. 1).

The particle beam extracted from the accelerator is modified by the degrader to have appropriate energy. Then it is broadened laterally by a double-scattering
Fig. 2. Passive beam shaping elements in a horizontal treatment room.

system to obtain a uniform, flat transversal profile (Schardt et al., 2010). The double scattering device contains a group of foils (first scatterer) situated at the beginning and a second bi-material gaussian-shaped scatterer placed farther. The second scatterer is often composed of high-Z material, which scatters more with little range reduction and a low-Z constituent that scatters less with more loss in the maximal distance (Paganetti and Bortfeld, 2005).

Afterwards the beam must be spread along the longitudinal axis in order to cover the total length of the tumor. The superposition of Bragg peaks, which is called SOBP (Spread-Out Bragg Peak) region, is generated by ridge filters or range modulator wheels.

A modulator wheel that contains several absorbers of increasing thickness rotates at a frequency of 10 Hz and thus changes continuously the Bragg peak range as a function of rotation angle. In the treatment of small cancers, for example uveal melanomas, rotating modulators are made of plastic, whereas large therapeutic fields require wheels constructed from the combination of low (carbon) and high-Z (lead) materials (Paganetti and Bortfeld, 2005). In some systems the whole SOBP might be shifted in depth by a set of absorber plates (the so-called 'range shifter') to obtain a desired range in the patient’s body.

In order to accurately irradiate an irregular tumor volume, patient-specific devices need to be precisely fabricated (Schardt et al., 2010). The collimator shapes the field area specified by the largest target contour. A proton beam is typically collimated by brass aperture, whose thickness must be greater than the SOBP range to ensure that particles from outside of the therapeutic field are effectively blocked (Kooy et al., 2008). The second custom-made element is the plastic range compensator. It adjusts the field to the distal contour of the target volume. A horizontal beam treatment room with passive beam shaping devices is shown in Fig. 2.

Although the passive beam delivery system is often used in particle therapy centers
all over the world, it has many significant disadvantages. The efficiency of a double-scattering system might be as low as 20 % (Paganetti and Bortfeld, 2005) because a substantial fraction of the initial beam intensity is wasted in the scatterer, apertures and blocking devices (Kraft, 2000). Furthermore, nuclear interactions between the particles and the material of the beam modifying elements lead to the production of light nuclear fragments and a large amount of mostly forwardly scattered neutrons, thus leading to the contamination of the beam (Jäkel et al., 2007). A third drawback is that in passive system the dose cannot be adjusted to the proximal end of the target volume. As a result a significant dose is delivered to the adjacent healthy tissue (Krämer et al., 2000). Another aspect is the need for manufacturing the compensators and collimators individually for each patient, which generates additional costs.

All these drawbacks have induced researchers to develop a new, more efficient method of delivering the beam to the tumor.

4. Active scanning

Active scanning techniques represent a totally different approach to cancer treatment. Instead of applying a broad beam, as it was done in the passive system, they use a narrow pencil beam. The tumor volume is subdivided into multiple layers, each of which forms a grid of voxels. The distance between neighboring voxels is about 2–3 mm (Jäkel et al., 2007) and the appropriate dose is delivered to these small spatial elements by the beam that is moved from voxel to voxel along a continuous path covering the entire layer (Kraft, 2000). Electromagnets are responsible for the deflection of the beam, as shown in Fig. 3.

Some systems apply the discrete scanning method, in which the beam is turned off after the irradiation of each single spot to alter magnet settings (Paganetti and Bortfeld, 2005). Other devices move the narrow beam within a single layer without interruption (Kraft, 2000). When the slice located at a certain depth is fully scanned, the energy of particles is changed and the irradiation is repeated for the next layer. The modification of beam energy can be done either by absorbers of different thickness (in case of cyclotron) or directly by the synchrotron. In case of carbon ions, kinetic energy range between 80 and 430 MeV/u corresponds to a range in the tissue between 2 and 33 cm respectively (Krämer et al., 2000). For proton beams, the energy is adjusted between 70 and 230 MeV, where the latter value results in the tissue penetration depth of about 32 cm (Paganetti and Bortfeld, 2005). The interval between
tumor slices must be less than half the width of the Bragg peak, which equals 5 mm for carbon ions penetrating the tissue deeper than 10 cm (Kraft, 2000). However, for beam energies below 150 MeV/u the pristine Bragg peaks are too sharp to maintain a reasonable distance between layers. A denser arrangement of layers would cause an increase in treatment time and necessitate highly sensitive scan monitor systems. Therefore, a comb-shaped ripple filter is used to slightly broaden the Bragg peak for low beam energies (Krämer et al., 2000). It is worth mentioning that the dose is delivered to a voxel not only by stopping particles, but also by particles going to deeper layers, which must be taken into account during the treatment planning process.

The completely active, intensity-controlled raster scanning represents the future of cancer particle therapy due to its numerous advantages. It irradiates any irregular tumor with a millimeter precision (Kubiak, 2013). Elimination of passive elements from the beam path reduces nuclear interactions outside the patient and thus neutron and secondary fragments beam contamination (Paganetti and Bortfeld, 2005). Additionally, the absence of patient-specific beam forming elements reduces treatment costs.

The main disadvantage of the scanning method is the increased sensitivity to organ motion, which is important during the treatment of tumors situated in the thorax or the abdomen. Systems for irradiating moving targets are still being developed.

Active scanning system has been initially implemented in Paul Scherrer Institute in Villigen (Switzerland) for protons (Zenklusen et al., 2010) and GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt (Germany) for carbon ions (Schardt et al., 2010). Currently, this technique is used in leading European cancer therapy facilities, for example Heidelberg Ion Therapy Centre (HIT) in Germany and National Centre of Oncological Hadrontherapy (CNAO) in Italy.

5. Particle acceleration systems

Protons and carbon ions for cancer therapy are often obtained using compact ECR sources based on the effect of Electron Cyclotron Resonance (Kubiak, 2013). Cyclotrons or synchrotrons accelerate the beams to appropriate energies. Isochronous cyclotrons, in which the orbital period is constant for particles regardless of their energy, provide stable and regular beam intensities. The main disadvantage of such systems is the fixed energy of the continuous beam from the cyclotron. Beam energy must be changed externally by a passive degrader, for example a multi-wedged carbon absorber, which is inserted in the beam line (Pedroni et al., 2004). Unfortunately, this process reduces the beam quality, i.a. due to scattering, and energy struggling.

Synchrotrons are more popular in carbon ion therapy centers. Particles are accelerated in resonant cavities by a variable electric field and their trajectory is bent by time-dependent magnetic field to maintain a constant radius in the circulation ring (Fig. 4).

The strength of the magnetic field is therefore changed synchronously with the increase in the kinetic energy of the beam. It is worth noting that the synchrotron delivers a pulsed beam with a specific repetition rate (Paganetti and Bortfeld, 2005). The unique possibility of changing the energy of the extracted beam from a pulse to pulse, which is necessary to alter the penetration depth without using passive absorbers, constitutes a great advantage of this device (Jäkel et al., 2007).
the high magnetic rigidity of carbon ion beams (for $^{12}$C 400 MeV/u, approximately three times higher than for protons of the same range) strong and thereby large and heavy magnets are need to achieve a reasonable bending radius (Jäkel et al., 2007).

The development of irradiation techniques for moving organs created the need for constructing accelerators capable of changing the beam energy very fast. 'Cyclinac' is a combination of a superconducting isochronous cyclotron (accelerating ions to a fixed initial energy) and a high-gradient linac (boosting the energy to the required values by turning off a specified number of independently controlled klystrons and varying the amplitude and phase of the drive signal dispatched to the final active unit) (Garonna et al., 2010). The technologies of protons and carbon ions acceleration used in therapy are still being improved.

6. Conclusion

Hadron therapy opens new perspectives in the fight against cancer. The Bragg maximum at the end of the proton and carbon ion range delivers a higher dose of radiation to the tumor and ensures the maximum protection of healthy tissues. An optimal choice of a beam delivery system is needed to fully exploit the benefits of the particle therapy. Although passive beam forming systems are still used in many medical centers, active pencil-beam scanning techniques, which allow highly conformal treatment, are a better option for the future.

References


