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PHYSICAL BASIS OF PROTON RADIATION THERAPY IN MEDICINE

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Abstract:
The work considers the history of using proton irradiation in medicine and the disadvantages of photon radiation therapy. The physical basis of proton therapy is shown according to the graph of tissue proton absorption, in which the Bragg peak's position can be adjusted using proton energy. It is shown that proton therapy for the treatment of lung cancer is one of many therapies, due to its unique physical and biological properties.

Keywords: Proton, therapy, tumor, safety, photon, tissue, Bragg peak, cancer, physics, beam.

Introduction

Proton therapy is a radiation therapy that uses tiny particles called protons. Protons are excellent cell killers, but because of the way protons deliver their energy, proton therapy does not damage as much healthy tissue as photon

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therapy. Therefore, a higher dose of radiation can be directed at a tumor without affecting many normal healthy cells.

The first use of a proton beam to irradiate malignant tumors was proposed by R.R. Wilson of the Harvard Cyclotron Laboratory in a paper published back in 1946. It described the basic principles of proton absorption in tissue and clearly presented the theoretical advantages of the technique. Its first real clinical application was in 1954, when the first patient was irradiated at the Berkeley Radiation Laboratory in California. In Europe, the first case of treatment was registered in a clinic in Uppsala (Sweden) in 1957.

However, at that time the technology was very complex and the insufficient ability to accurately determine the target of exposure and the direction of the beam were an obstacle to the further development of proton therapy. For several decades, it remained a rather secondary part of physical research.

The turning point came with the improvement of photon radiotherapy technology, which was relatively quickly introduced into practice as proton therapy.

In 1990, the first clinic was opened at Loma Linda University Medical Center (California), intended exclusively for clinical use. In the new millennium, approximately 2-3 centers are opening per year.

However, to date, the study of the possibilities of standard photon radiotherapy leaves a number of questions:

1) insufficient effectiveness in the treatment of a number of pathologies;

2) safety of "delivery" of an effective dose directly to the tumor;

3) delayed and late side effects of treatment caused by unwanted irradiation of surrounding healthy tissues. Proton therapy comes closest to achieving this goal of all available methods.

Proton therapy is a revolutionary method in radiotherapy that uses different physical interactions than photon therapy to deliver the radiation dose to the tumor, but identical radiobiological principles to achieve the therapeutic effect.

This greatly simplifies the management of the treatment process using optimal methods of "delivering" the dose to the tumor. Proton therapy is thus considered a "new medicine" from the point of view of physics, but not from the point of view of radiotherapy.

It is known that protons, when passing through tissues, transfer their energy along the path only to a small extent. Protons transfer their maximum energy at the end of

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their path – in the so-called Bragg peak (BP, a region several millimeters wide). The depth of the BP is precisely determined by the particle's input energy. After transferring energy, the particle stops in the tissue. This results in a relatively low radiation dose in front of the tumor site and zero dose behind the tumor site (Fig. 1).

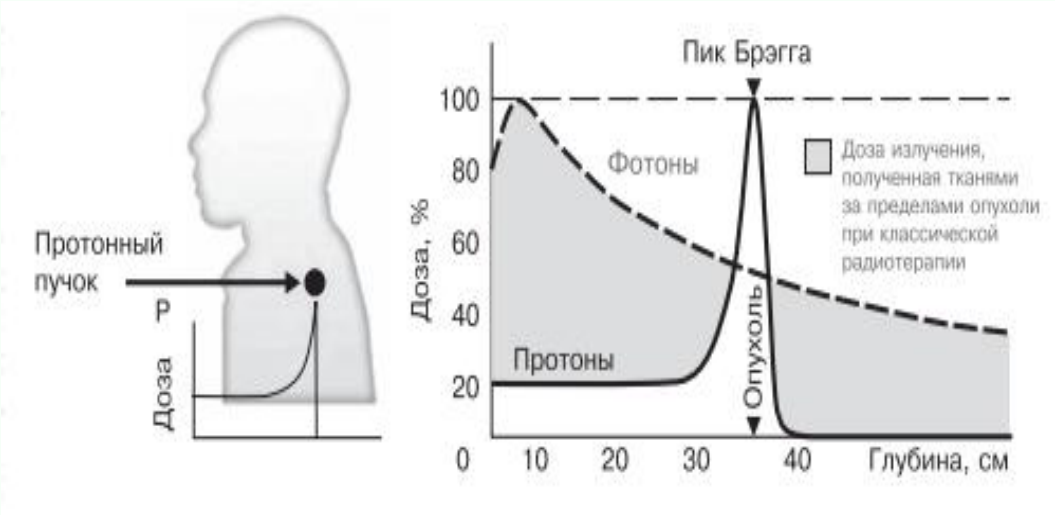

Fig. 1. Graph of proton absorption (blue) by tissue versus tissue depth. For comparison, a graph of photons (gray) is shown. The position of the Bragg peak can be adjusted using proton energy.

However, to irradiate a tumor lesion, it is necessary to expand the peak area in relation to the lesion, i.e. to create an extended PB (spread-out Bragg peak – SOBP). This can be achieved using “passive” scattering or using a scanning beam.

The first option is still the most common due to historical development, but there is already a technology in the world that is superior in accuracy. For active scanning of SOBP, a Range modulator is used.

The resulting beam must be processed using individually manufactured aperture devices and a Range compensator. Compensators are individually made of plastic for each patient on processing machines.

The apertures are made of brass and define the lateral edge of the field. Their production is a labor-intensive and expensive process, and their use in treatment results in a significant radiation load on the staff and the patient. In addition, this method does not guarantee precise irradiation at the edge of the target. A technologically revolutionary method in proton therapy is the pencil scanning

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technique. A proton beam with a diameter of several millimeters "scans" the target layer point by point using magnets. After irradiating one layer, the beam energy changes and scanning of the next layer continues (Fig. 2).

Fig. 2. Illustration of pencil scanning technology.

The main advantages of this technology are the targeted delivery of radiation dose to the tumor target and a significant reduction in radiation exposure to personnel.

Proton therapy can be effective in treating many types of tumors, including those of the brain, head and neck, central nervous system, lung, prostate, and gastrointestinal tract. Proton therapy is often the preferred option for treating solid tumors in children because protons can be precisely controlled to reduce radiation exposure to normal tissue, helping to prevent serious complications and reducing the likelihood of secondary tumors. Proton beam therapy is the preferred standard for many tumors including:

• Tumors of the eye, including intraocular melanomas
• Tumors that are near or at the base of the skull, such as chordoma and chondrosarcomas
• Tumors of the spine – primary or metastatic
• Hepatocellular carcinoma
• Solid tumors in children – primary or benign tumors in children
• Tumors of the brain and spinal cord – malignant and benign
• Advanced and/or unfavorable head and neck cancers such as Cancer of the paranasal sinuses and other paranasal sinuses; eg, adenoid cystic carcinoma, Advanced nasopharyngeal cancer, Advanced buccal mucosa cancer
• Retroperitoneal sarcomas

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• Re-irradiation cases – when radiation is being considered for a second or third time to the same site.

There is now ample evidence from the sites mentioned above that proton therapy has some benefit. However, many other cancers may also benefit from proton therapy, especially when compared to conventional X-ray therapy. These include:

• Esophageal cancer
• Breast cancer
• Oropharyngeal cancer
• Salivary gland cancer
• Lung cancer
• Prostate cancer
• Sarcomas
• Skull base tumors

Proton therapy for lung cancer is one of many exciting advances in the field. Despite the best advances in photon therapy such as IMRT, IGRT, Cyberknife, Helical Tomotherapy, the doses to the heart and lungs are sometimes prohibitively high. Even if the dose is within thresholds, there is significant cardiopulmonary toxicity, resulting in significant morbidity (up to 80%) and even mortality (up to 5%). Proton therapy, due to its unique physical and biological properties, can deliver significantly lower doses to critical structures such as the healthy lung as well as the heart, thereby limiting collateral damage.

The best way to understand how proton therapy works is to look at the physics and engineering inside a proton accelerator, or cyclotron/synchrotron, and the beam delivery system.

• A proton begins its journey in the ion source. Within a fraction of a second, the hydrogen atoms are split into negatively charged electrons and positively charged protons.

• The protons are injected through a vacuum tube into the linear accelerator, and in just a few microseconds, the protons reach an energy of 7 million electron volts.

•The proton beams remain in the vacuum tube, entering the cyclotron/synchrotron, where acceleration increases their energy to a total of 70 million to 250 million electron volts, enough to place them at any depth in the patient's body.

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• After leaving the synchrotron, the protons pass through a beam transport system, which consists of a series of magnets that shape, focus and direct the proton beam to the appropriate treatment room.
• To ensure that each patient receives their intended treatment safely and effectively, the facility is monitored by a network of computers and security systems.
• The gantry can rotate 360 degrees, allowing the beam to be delivered at any angle.
• As the protons pass through the nozzle, a system of electromagnets positioned perpendicular to each other bends each beam so that they reach the planned position deep within the tumour. This is called pencil beam scanning (PBS).
• At Apollo Proton Cancer Centre, we have the latest PBS technology, which allows us to deliver highly targeted treatment to each tumour, with each tumour treated with protons point-by-point and in layers.
• At maximum energy, a proton beam travels 125,000 miles per second, equivalent to two-thirds the speed of light. From the ion source to the patient, a proton typically travels 313,000 miles.
• Once a proton enters the body, it slowly increases the energy deposited in the tissue until it reaches a certain depth, where it deposits almost all of its energy and stops. This effect is called the Bragg peak effect.

Thus, unlike an X-ray beam, which passes through the entire body, a proton beam actually stops at a certain depth inside the tumor. By manipulating the energy of the proton beam and the position of the spot, the tumor is treated with a high dose of radiation, while the surrounding tissues are spared from the radiation dose.

Conclusion: At the physical level, it is undeniable that proton therapy has much better parameters than most technologies available for photon irradiation. At the level of clinical results, there are only reasonable assumptions about the advantages of proton therapy, and its use is fully accepted only for some diagnoses. The modern development of proton therapy should go in the direction of stereotactic radiotherapy, which most fully uses the dosimetry advantages of protons and at the same time significantly reduces the cost of treatment.

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