Analysis of the Proton Therapy Controlling System and Application

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Abstract. In recent years, the cancel therapy remains a key issue that needs to be addressed for human beings. As a matter of fact, the proton beam therapy (PBT) is a new kind of way to treat tumor by emitting proton beam. Different from conventional radiation therapy, the main principal is to cut the DNA of the tumor cells and prevent further development. In this case, this study will discuss the proton therapy controlling system as well as demonstrate the applications. Comparing to the X-rays, protons can align tumors more precisely and decrease the effect of other normal tissues, which also decrease the side effects. Nevertheless, the proton therapy is still be developed further. Many proton centers are being built and will begin operating in the future. This article popularizes the basic knowledge of proton therapy, from the basic principle, the applications to the limitations. These results shed light on guiding further exploration of proton therapy.

Keywords: Proton beam, cancer therapy, tumor cell.

1. Introduction

The first idea about using proton the treat tumor was come up by Wilson in Harvard University in 1946. In 1954, the first patient case was conducted by Lawrence-Berkeley National Laboratory. Then, the first medical proton therapy facility was installed at Loma Linda University Medical Center in 1990. From then on, more proton therapy center was built and this technology was spread largely. In 1998, the American Food and Drug Administration give permission to the first proton therapy equipment, which makes proton therapy develop deeper. There were about 23 proton centers all around the world since 2004. The center which treats the most patients is LLUMC in Loma Linda in America, in about 9280 people. In 2022, the first proton therapy controlling system was appeared on the market in China [1].

As for the clinical progression, the data shows that proton therapy has a good effect in different tumors. For example, the primary hepatic carcinoma, about 87% of the patients can control their tumor for 5 years. For the head and neck neoplasm, the total controlling rate is 95% and the survival rate is 90% [2]. Till now, this concept has developed for different forms with different techniques, such as the Passive scattering technique and the Beam current scanning technique. As a new technology, the proton therapy has huge potential to make a large contribution in medical field. However, it still has many problems and obstacles.

This article aims at popularizing some knowledge about the proton therapy, including the basic description of proton therapy, the principal of proton therapy, some facilities, applications, limitations and the future outlooks. There will be some physics-based principals, the application workflows and practical use.

2. Basic Description of Proton Therapy

2.1. Bragg Peak Characteristic

Protons have a physical characteristic called Bragg peak characteristic, which means that protons are deposited in small doses along the transport route but are largely deposited at the end of the range. This makes proton therapy suitable for treating tumor since it can irradiate the diseased part

intensively and has little side effect to the normal organs and tissue [3]. According to the research, the normal cells including skin in front of the tumors only receive about 1/3 to 1/2 of the maximum dose, and the normal cells behind the tumor are basically unaffected [4].

2.2. Sperading the Beams

The normal beam emitted by the accelerators does not has enough dispersion to have a Bragg peak which is wide enough to cover the thick tumor. Therefore, it is important to control the energy of the beam and find some ways to expand the width of the Bragg peak.

By using an energy modulation wheel, which consist of different stages with different height and width. When this wheel rotates in a constant speed, the proton beam passing through it has lower energy level and construct a smaller Bragg peak. The smaller Bragg peaks gather together to form a larger Bragg peak which has certain energy level and wider range than one beam. This can construct a suitable explosive time for certain tumor in certain width [5].

It is an early technology. The principal is to add scatterer in the route of the proton beam. The scatterer has high atomic number, which can scatter the proton beam in horizontal direction by the principal of the scattering between protons and nucleus. Additionally, there are two gadgets called range compensator and collimator, which increasing the evenness and adaptiveness of protons. However, because the different size of rumor must have different range compensator and collimator, this method needs huge manpower and material resources. For the rumor that has complex shape and surroundings, the suitability for it is still relatively poor. Spot scanning is one of the techniques in dynamic scanning. The principal of this technique is to divide the tumor into different equal energy level and irradiate by the protons with same amount of energy. The operation begins with the deepest tumor layer and irradiates layer by layer [6]. One of the spot scanning technique is the pencil beam scanning system. The method is to add a quadrupole magnet and a couple of orthogonal curving magnet to make proton beam deflect. The ionization chamber detect the beam direction and feedback to the controlling system. Then the controlling system control the magnetic field and the proton beam, in order to launch precisely. This method is more accurate and quicker, which has become the principal way to treat tumor [7]. From an experiment that comparing between the extended beam which using Passive scattering technique and the pencil beam, the result was given in order to compare the beam scattering to the environment. Two experiments were repeated in an extended beam treatment room and a pencil beam treatment room by using simulated tumor, and did the beam detection in beam output window and treatment couch isocenter (seen from Table 1 and Table 2).

Table 1. Induced radioactivity dose rates of extended beam at the beam output window and treatment couch isocenter (μSv/h)

Measuring sequence	Beam output window	Treatment couch isocenter
1	32.3	4.5
2	63.2	5.6
3	70.1	7.7

Table 2. Induced radioactivity dose rates of pencil beam at the beam output window and treatment couch isocenter (μSv/h)

Measuring sequence	Beam output window	Treatment couch isocenter
1	3.2	0.21
2	2.3	0.18
3	2.1	0.18

From the testing result, the induced radioactivity dose rates of pencil beam are far less than that of extended beam. As a result, using pencil beam can better protect the patients and the stuffs. Although the passive scanning technique is easy to use and still be used by many proton centers, the pencil beam has already showed its potential and may be used broadly in the future [8].

3. Principal of Proton

Proton therapy is a very precise radiation therapy for tumors Instead of X-rays, as is usually the case, the beam is made up of high-energy rays made of protons in the top layer, allowing tumors to be more accurate with their X-rays. In contrast to other approaches, the energy is focused on the tumor itself, on surrounding unhealthy tissue and completely eliminating tumor cells one by one. Strahlentherapie Energiestrahl is placed in the patient's body, through the tumor on the other side and back again. The separation of vaccines, similar to the treatment of "test-tube input" radiation, can cause harmful effects on healthy tissues outside the brain.

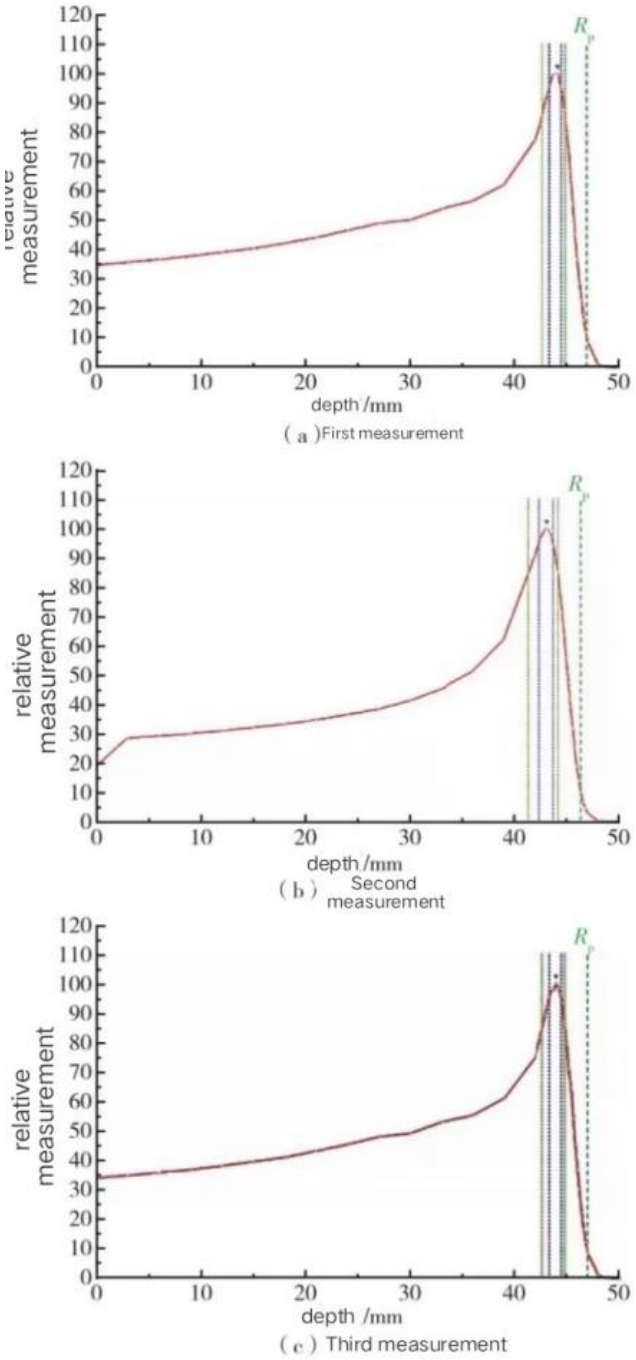


Figure 1. The relative measurment as a function of depth: (a) first, (b) second and (c) third.

A proton is a particle larger than the actual radioactive material used, capable of releasing a greater amount of energy in a tumor. However, protons enter the body very quickly, so the possibility of a proton interacting with a cell is very small because of the speed at which it enters the body. Once it slows down and stops, the protons release energy and interact with the cell So, when we use proton

therapy for clinical treatment of tumors, we input the energy of the protons in advance, and then control the energy content of the protons when they enter the body, so that they stop at the desired location. This energy peak is called the "Blake Peak", and the "meter Solid center Navigator" data analysis function is also used to calculate the radiation crest, reference depth, peak, actual distance, and remaining distance. The brag peak of ranging refers to 95% of the highest dose, with a reference depth in the brag peak area center. At maximum depth 4 high temperatures, we determine the percentage of freezing point contamination on the central axis of the tank and plot the corresponding curve. When the energy is transferred to the tumor, the protons stop, do not leave the tumor tissue, and do not enter The average brag peak and the base of the three indicators were 1.21 mm and 43.63 mm respectively (seen from Fig. 3) [9]. This approach can reduce the amount of radiation exposure and the amount of damage that proton beam therapy can cause to healthy tissues, especially sensitive areas such as brain, eyes, spinal cord, heart, thick blood vessels and nerves. In proton beam therapy, it is necessary to ensure that the proton beam hits the target. Therefore, with each treatment, the patient may have to undergo an imaging test, such as computed tomography or MRI, that provides an image of the tumor and its surroundings. The treatment team may mark the patient to indicate the site of treatment, but it may take a few minutes to adjust the patient and instruments to ensure that the proton beam reaches the right place in the tumor. In proton beam therapy, it is necessary to ensure that the proton beam hits the target. Therefore, with each treatment, the patient may have to undergo an imaging test, such as computed tomography or MRI, that provides an image of the tumor and its surroundings.

4. Facility

Proton therapy is a highly accurate radiation therapy for cancer and other diseases Unlike traditional radiation therapy, proton therapy uses X-rays instead of protons. A proton is a negatively charged charge that controls the depth and energy balance of the injection. One needs a proton therapy therapy that can hit the tumor with precisely the right amount of radiation to prevent damage to the surrounding healthy tissue. Proton therapy equipment typically includes accelerators, proton radiation protocols, treatment plans, and treatment beds. The booster accelerates high-energy proton rays by injecting protons close to the speed of light The proton beam will be delivered to a target area in the patient's body through a collider and radiometric tracking system. Radiation protection requires that the main components of the proton therapy equipment must be poured with heavy concrete, and large stone ash must be used during construction to prevent the drums from filling or leaking oil. In addition, the area of the multi-layer treatment network is large, so it will be used from the perspective of post-run-in and structure, and special attention will be paid to the design and process of post-run-in. The objective of this measure must be strictly observed in order to avoid cracks between the new and old Gerinnungsmitteln, otherwise it would be easy for groundwater to enter the room which could be excavated after the leak, and it would also be difficult to repair the many Protonentherapiegerate needed in the concourse here. In order to optimize the configuration of the pipes in the concrete, the connections between the pipes should be considered sealed and waterproof, otherwise there is water in the pipes, so it is difficult to determine the cause of the leakage. If one can't fix it, one plugs it Therefore, enough absorption tubes can be used to increase the amount of charger, while making the drain water resistant. Most of the areas covered by the proton beam (walls, ceilings, soil) are resinized to remove dust. Medically, if you can install proton therapy on the ground, it can cause severe burns. It is recommended that the surface be lined up at one level before installation, and then removed before installation. Walls and ceilings can be repainted before installation [10].

At present, there are six suppliers of proton therapy equipment in the world, including BA Company of Belgium, Jia Fa Company of Japan, Hitachi Company of Japan. Japan's Sanmai Company, the United States Optivie company and Aecays company [11]. Accelerators that use DC high-voltage electric fields for acceleration have lower energy, and accelerators that use induced vortex electric fields for acceleration can only accelerate electrons. Proton therapy requires higher

energy protons, which can only be obtained by high-frequency resonant accelerators. In general, in order for proton beams to treat tumors with a depth of 30cm to 315cm, a proton accelerator of 70 to 230MeV is required.

Proton accelerators are basically the following types:

- Synchrotron
- Cyclotron
- Synchrocyclotron
- Linear accelerator.

The superiority of these accelerators has always been controversial. The biggest advantage of the cyclotron is that it is easy to operate, but it requires an additional energy selection system, because it does not have energy tunability, and its beam quality is not as good as the other two types of accelerators. The advantage of synchrotron is that the output energy is adjustable, and there is no need to configure the energy selection system, but it is more complex to operate and occupies a large area. The linear accelerator can also achieve adjustable output energy, and its beam quality is particularly good. In proton therapy, protons of different energies should be used according to the depth and thickness of the tumor itself, and the proton stream energy derived from the cyclotron is fixed, so there is an energy selection system between the accelerator and the treatment head, which is composed of various magnets and measuring elements for energy reducers and ion optics. When the proton passes through the graphite layer, the larger the graphite thickness, the greater the energy reduction, so different thicknesses can be used to obtain different energy reduction. When the 230MeV fixed energy protons extracted from the accelerator enter the energy selection system, by adjusting the different thicknesses of the energy reducers, a continuous and adjustable flow of protons of different energies from 70MeV to 230MeV can be obtained at the output end.

The task of the beam transport system is to deliver the proton beam generated by the accelerator near the patient's treatment site. A quadrupole magnet, a deflection magnet, a guide magnet, a beam measuring device and a vacuum device are placed along the beam transport pipe. The job of a quadrupole magnet is to focus a beam of protons. The task of the deflection magnet is to change the direction of the beam. The task of the guiding magnet is to correct the deviation caused by the proton beam when the system is installed.

Patients often need to be positioned in the treatment room for a longer period of time, and in order to make full use of the beam of the accelerator, proton therapy units are usually configured with multiple treatment rooms, each of which is staggered in irradiation time. The treatment room is divided into a fixed beam treatment room and a rotating beam treatment room. The rotating beam treatment room is equipped with a rotating frame that can rotate around the lying patient so that the proton beam can irradiate the target area from different directions. The proton beam from the accelerator is advanced to the main beam line and then transferred to a different branch line as needed to enter the treatment room. The junction of the main beam and the branch beam is equipped with a deflection magnet to change the beam direction, which is also called a switching magnet.

In order to expand the beam induced by the accelerator into a large and uniform proton stream covering all the transverse areas of the tumor, a beam distribution system is required. In order to form an extended Bragg peak that can illuminate the entire longitudinal depth of the tumor, a beam energy modulator is required. All of these special functional components, a total of more than a dozen are installed in the treatment head. For example:

- Energy reducer: used to greatly reduce proton energy, the commonly used energy reducer is a graphite cylinder, plus stainless steel shell as protection.
- Rotational modulator: used for the range modulation of proton beams.
- Binary energy modulator: used for fine range modulation.
- Range compensator: Ensure that the extended Bragg peak falls exactly on the rear boundary of the target area.

- Scattering system: Currently the most widely used beam expansion system, of which the single scattering system is only suitable for the irradiation field is very small, and a large number of applications are double scattering systems.
- Collimator: used to limit the irradiation field, generally equipped with a range monitor to monitor the proton range.
- Positioning system: used to make the proton beam accurately radiate at the tumor lesion site.

In order to ensure that the real proton therapy dose parameters during treatment meet the prescribed therapeutic requirements, while ensuring safety and efficacy, a dose verification system must be set for real-time monitoring of therapeutic dose. Treatment planning system: The essence is a software dedicated to proton therapy, the doctor according to the patient's relevant diagnostic information, with this software to develop the patient's treatment plan, and determine the operation parameters of the device. Treatment control system: each device in the proton therapy system that independently completes a specific function is connected together, and all devices work in coordination according to treatment requirements through special application software. Treatment safety system: used to ensure that patients and medical personnel are not harmed by radiation.

5. Applications

The control system already has many applications in the field of radiotherapy for the treatment of tumors, not only in proton therapy, but also in conventional x-ray therapy. In this text, some of the applications in proton therapy and in conventional x-ray therapy will be described. The first example is the dynamic power control system for proton therapy devices in Shanghai. In order to deliver proton beams of different energies to the patient, the system must rapidly change the magnetic field. The different energies of proton beams required for patient treatment are achieved mainly by controlling about 30 dynamic power supply currents located in the main ring of the synchrotron to rapidly change the magnetic field of the corresponding magnets.

Due to the eddy current effect that occurs in the pole plates of the magnetic field, a delay in the magnetic field occurs. The immediate solution to this problem would be to redesign the pole plate material and structure, but this would be too time consuming and costly, so the solution to this problem is to generate a current overshoot when the magnetic field generated by the current supply is close to the desired strength, accelerating the magnetic field to a set value and reducing the time required for the magnetic field to lag behind. This current callback is different from that caused by the underdamped characteristics of conventional current, because the overshoot of conventional current is unstable, but because the proton therapy characteristics dictate that the energy of the generated proton beam must be stable, the power supply current strength is not allowed to fluctuate after the magnetic field reaches the set value, so the power supply current can be allowed to operate in a single cycle with a special waveform [12]. The second example is the heavy ion therapy technique, where the position of the bragg peak strictly corresponds to the heavy ion beam energy, which requires that the heavy ion beam energy be converted in different intervals [13]. Medical electronic gas pedal consists of electron gun, accelerating tube, high frequency system, vacuum system and cooling system, which is operated by electronic control system, modern medical electronic system are all digital system, electronic computer as the core, programmeable logical controller and distributed control system has been widely used, distributed control system has been Widely used, the initial goal of dcs is to simplify the complex large-scale control system, and now it is already a mature software with layered design and standardized interfaces.

The core idea of the control system is to digitize the bottom control model and establish a standardized middle layer control signal database, so the structure of the system is a client server structure, the client server structure is divided into two kinds: thin client and thick client structure, thin client structure for the In this structure, the thin client only needs to send a request to the server, and the server will reply, while in the thick client structure, part of the data will be stored in the client, and the client will carry out part of the calculations, so the ssd, hdd, ram, and other data will be stored

in the client, and the data will not be stored in the client, so it is not necessary for the system to be stored in the client. roms of the client are high [14].

6. Limitations and future Prospects

Proton therapy, as an emerging treatment, naturally has its shortcomings. In this text, we will discuss the shortcomings and development prospects of proton therapy. The shortcomings of proton therapy are divided into two parts; the first part is the types of cancers that are not suitable for proton therapy, and the second is the price. Proton therapy, as a particle therapy, is quite different from traditional radiotherapy in that it will use the Bragg peak as a feature for precise treatment, as mentioned in the text above, which at the same time poses many problems, such as when the exact location of the tumour cells cannot be determined, as in the following case.

Firstly, the cancer has been widely metastasised all over the body, at this time the treatment plan should be systemic systemic treatment mainly, and proton therapy cannot solve the problem of large area cancer. The second type is the pathological type of cancer is unknown, when the patient hasn't done pathological biopsy, the doctor can't confirm the exact problem of cancer, then proton therapy can't be carried out for accurate treatment. Haematological tumours such as leukaemia and multiple myeloma. The fourth type is cavity organ tumours, such as stomach cancer. This kind of strange is not suitable for proton therapy because it is in a peristaltic state and its precise location cannot be determined, which makes it extremely difficult for proton therapy that requires very high precision reading for irradiation. The price problem comes mainly from the high price of instruments and the high competence required of doctors.

Typically, the construction of a proton centre often requires billions of RMB, with a construction time of two to five years, and a lot of money for the annual maintenance costs that follow. Often a proton therapy device will be installed together with other new technologies, gantry being one example, and adding a gantry will cost an additional RMB 100 million, with annual maintenance costs of nearly RMB 10 million.The future development of proton therapy can be summarised in the following categories: personalised treatment, expansion of applications, and cost reduction. Personalised therapy refers to the fact that more accurate tumour localisation, tissue characterisation and dose calculations allow for more refined treatment planning, improved efficacy and fewer side effects. Expanding the scope of application refers to the fact that proton therapy is expected to expand its application to cover more types of tumours with the advancement of technology and in-depth clinical research. Cost reduction means that the cost of preparation will decrease, making proton therapy more feasible and affordable.

7. Conclusion

The advantages of proton therapy are small side scattering, strong penetration performance, good dose distribution and high local dose. During treatment, high-energy proton beams enter the body at a very high speed. Due to the high speed, the chance of interaction with normal tissues in the body is extremely low, so it can effectively protect normal tissues. The current research aims to improve the therapeutic potential of proton therapy, including identifying and mitigating the effects of physical uncertainties on proton dose distribution through advanced image-guided and adaptive radiotherapy techniques. As residual uncertainties remain, robustness evaluation and robustness optimization techniques are currently being developed to make dose distributions more resilient and improve confidence in them. Ongoing research also includes improving our understanding of the biology and immunomodulatory effects of proton therapy. Such studies, along with continued technological advances in planning and launching methods, are likely to help demonstrate the superiority of protons. The significance of this study is to understand proton therapy in various aspects, and to dig deeply into the principle and future of proton therapy from various angles.

Author Contribution

All the authors contributed equally and their names were listed in alphabetical order.

References

[1] Li W. Advances in proton and heavy ion tumor therapy. Nuclear Physical Review, 2005, 1.

[2] Ji Z, Jiang Y, Wang J, et al. Research progress of clinical application of proton radiotherapy. Western Medicine, 2016, 28 (4): 580 - 584.

[3] He S. Localization algorithm of proton beam Bragg peak in proton therapy. Wuhan University, 2019.

[4] Liu S. Physical properties and working principles of proton therapy. Knowledge of Modern Physics, 2003, 15 (2): 28 - 32.

[5] Fang C, Hou J, Xu S, et al. Principle and application of proton therapy system. Chinese Medical Equipment, 2021, 4: 187 - 192.

[6] Jia Y, Li Y, Zhang X, et al. Simulation of proton therapy midpoint scanning irradiation technique. ACS report, 2016, 1: 10.

[7] Choi S, Zhang J, Lu X, Hu M. Development and challenges of proton therapy. Chinese Journal of Medical Physics, 2016, 202: 5.

[8] Song T, Wang Y, Sheng X, et al. Radiation dose induced by extended beam and pen beam in medical proton accelerator. Chinese Journal of Medical Physics, 2018, 12: 15.

[9] Wang J, Liu Z, Zhao L, et al. Review of large vision models and visual prompt engineering. arXiv preprint arXiv:2307.00855, 2023.

[10] Lu Y. of Neurological Disorder, from Molecular Neurobiology to Clinical Therapy. Mol Neurobiol, 2012, 46 (1): S1 - S99.

[11] Liu S. Analysis of the proton therapy. Institute of High Energy Physics, Chinese Academy of Science, 2017.

[12] Jiang G, Tan S, Zhao H, Chen G. Dynamic power supply controls in Shanghai proton therapy facility. Nuclear technology, 2018, 41 (2): 020404.

[13] Cong Y, Xu S, Li S, et al. The high frequency control system of heavy ion therapy device was developed. Review of Atomic Physics, 2019, 36 (1): 55 - 61.

[14] Du X, Liu D, Shen L, Chen J. Design of medical electron linear accelerator control system based on programmable logic controller and distributed control system. Chinese Medical Equipment, 2016, 13 (1): 16 - 18.