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Simple Equipment for Effective Utilization of a Proton Accelerator for Medical Purposes

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We propose the use of a proton beam from any type of accelerator and a complex system for transporting the beam into three procedure rooms not containing gantries with the aim of decreasing the cost and dimensions of large-scale radiotherapy centers and improving their quality. Each procedure room has facilities to select the direction of irradiation over a quite wide range, with active distribution of the dose into the target volume and use of a mobile tomograph at the site of irradiation.

Introduction

Proton and ion beam therapy has fundamental physical advantages over standard treatment with γ beams. It provides more accurate and uniform irradiation of targets adjacent to radiation-sensitive organs, with significant reductions in the irradiation of healthy tissue. It is therefore irreplaceable in the treatment of ocular tumors and in the treatment of children and minimizes the induction of delayed adverse events.

All contemporary proton and ion beam irradiation centers use costly and bulky equipment for particle acceleration and transport [1-3], and only 1% of patients in whom treatment is useful can expect to receive this treatment at the present time or in the next five years.

Proton (and ion) beam therapy will come to the fore in future years when placed against other types of radiotherapy if the equipment provides for a choice of useful particles, selection of irradiation direction, conformal and accurate determination of the biological dose received by targets of complex shape and taking cognizance of their surroundings; this is achieved by scanning (intensity-modulated proton therapy, IMPT) by using a tomograph at the site of irradiation. The apparatus must be reliable, safe, and convenient for doctors to use. It must be sufficiently compact and lightweight for it to be used in normal buildings. It must provide sufficient annual productivity and be sufficiently economical for patients for the cost of courses of treatment to be comparable with that of treatment on a γ apparatus.

The current cost of each fractional dose of irradiation with γ-quantum, proton, and ion beams is around 600-1100-1600 EURO, each treatment cycle consisting of 20-30 fractions. Thus, there is a need to decrease the cost of proton treatment by about a third.

Objectives

The aim of the present work was to find realistic ways of decreasing the cost of the apparatus for proton beam radiotherapy. We did not address the most complex and expensive part of the equipment – the accelerator – and did not touch on the standard devices and programs which are used with success in proton therapy. We considered only the potential for producing significant reductions in the size and cost of the apparatus used for transporting useful beams from the accelerator to patients. The main idea of the study consisted of developing not an ideal apparatus which would provide irradiation to any target over the shortest possible time and the highest possible accuracy, but an apparatus able to preserve the main advantages of proton therapy over γ therapy for the majority of patients.

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Proposals and Results

The treatment of small and deep targets with ion beans irradiates healthy tissues less than proton beams. In the treatment of large and shallow targets (as in about half of patients), the therapeutic actions of ion and proton beams are comparable [4]. The accelerator and all magnetic channels for transporting proton beams to patients are about three times more compact and inexpensive than those for ion beams. Thus, it can be suggested to consider only proton beams as feasible for use in the most compact and least expensive irradiation center for large-scale therapy.

In recent years, the introduction of proton therapy into small hospitals has been based on the proposed use of "single-cabin" centers with gantries [5-8]. However, for an irradiation center to have high productivity, the useful beam from a single accelerator must be used in several, for example three, procedure rooms [3].

The greatest difficulty in developing equipment for proton or ion beam therapy is associated with the systems for selecting the direction of irradiation of immobile supine patients with active dose distribution. These systems are gantries. Within the gantry, the bundle is turned and focused by magnets attached to a mobile frame. The natural solution to minimization of the size and power of the accelerator and the transport system is to use superconductors. Contemporary cyclotrons can be made using compact superconducting magnets [3], though optimum active dose distribution needs rapid changes in beam energy both in the useful beam generation system and in the beam transport systems (including gantries), where the beam energy must be changed rapidly. Superconductivity is therefore of little help in gantry design [9]. Despite many years of effort by scientists and engineers, gantries are very large, energy-consuming, and expensive constructions even at the design level (the weight and size of contemporary gantries for proton beams are about 100 t and 10 m^3, respectively. If a single accelerator is used to provide irradiation in three rooms with gantries, their contribution to the total cost of the equipment and business is more than 50%.

In 2016, doctors at MGH (Boston) analyzed treatment results from 5300 patients over a period of 10 years at their center fitted with two gantries [10]. They doubted the need for using classical gantries and formulated new requirements for the apparatus changing the direction of irradiation. The conclusions of this study indicated that the irradiation center in each procedure room needs to be stationary, though different fractions can be delivered with the patient in different positions and different directions of irradiation. This requires use of active scanning and CT at the irradiation site. There should be the possibility of changing the direction of illumination for each fraction, though the selection can be limited.

This study did not use versions of gantry systems previously proposed by the author [11], each of which had significant advantages over traditional systems. For example, a gantry with a stationary irradiation center and "division of the last magnet" for proton beams had a design diameter and weight of 8 m and 50 t instead of 10 m and 100 t. In an "eccentric" gantry, all the moveable heavy magnet apparatus had the same weight with a diameter of 2 m rather than 10 m, and the procedure table with the patient lying immobile upon it is rotated simultaneously with the magnets with a large radius (for example, about 2.5 m). However, doctors traditionally dislike the idea of moving a horizontally fixed patient, and these versions are not used.

Recent studies have proposed new versions of a simple and compact apparatus providing high-quality irradiation of an immobile patient from different directions without using a gantry.

Use of a stationary horizontal beam with irradiation of a seated (or standing) patient rotated around the vertical axis passing through the center of the target was proposed for irradiation of targets in the head and neck [12, 13], with monitoring of body and target shape directly at the irradiation site with a vertically moving tomograph (see Fig. 1). This apparatus does not contain heavy, expensive magnets and can be positioned in a room of small size (4 × 5 × 6 m).

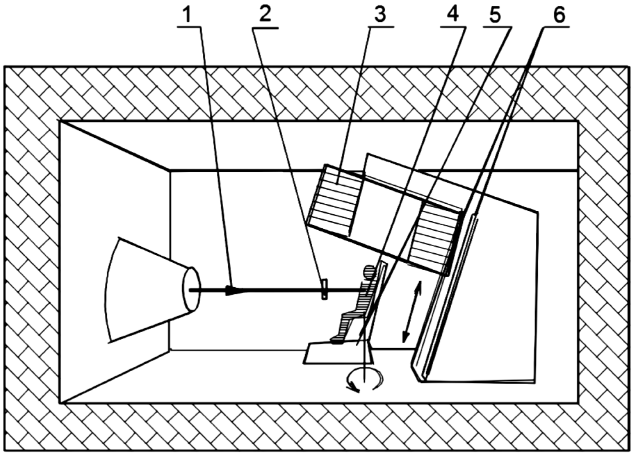

Fig. 1. Diagram of apparatus for irradiation of targets in the head and neck with rotation of the sitting patient around the vertical axis: 1) stationary horizontal beam; 2) beam-controlling apparatus; 3) tomograph on rails, moves to the operating and safe positions; 4) patient; 5) tilted chair with patient, can rotate around the vertical axis; 6) rails for tomograph.

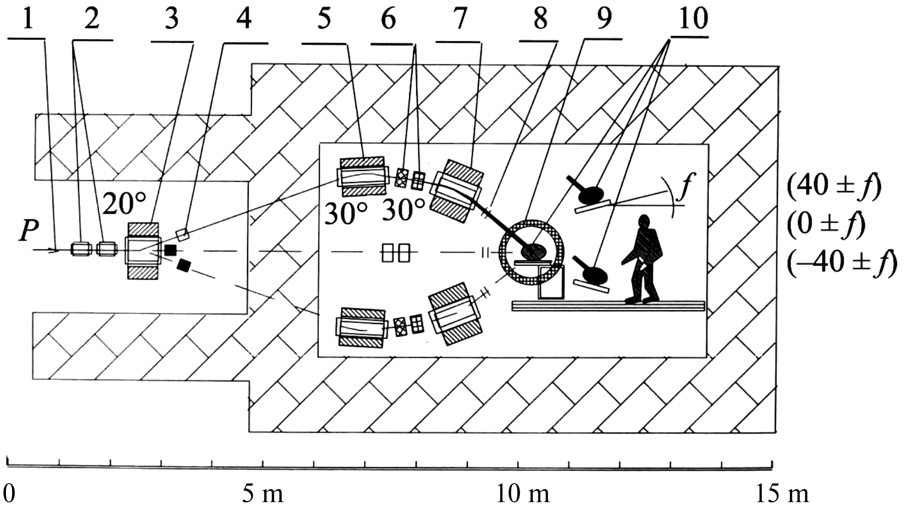

Fig. 2. Diagram showing flat system (with stationary irradiation center and small rotations of table): 1) horizontal input beam; 2) quadrupole lenses; 3) transfer magnet with beam turning in the vertical plane; 4) collimators; 5) magnets for turning the beam through 30°; 6) scanning magnets; 7) magnets for turning the beam through 30° with increased clearance; 8) beam-recording equipment; 9) tomograph moveable horizontally along the table bearing the patient; 10) position of patient on procedure table with the table in different orientations for different fractions.

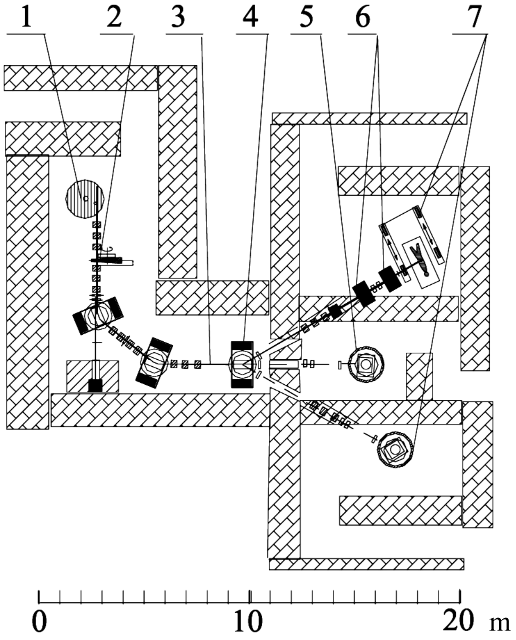

Fig. 3. Diagram of a proton irradiation center based on a cyclotron: 1) cyclotron; 2) filter changing mean beam energy (“degrader”); 3) useful beam; 4) magnet turning the useful beam in the direction of one of the procedure rooms; 5) procedure room containing patient sitting in a rotating chair; 6) procedure room with flat system with stationary irradiation center; 7) moveable tomographs.

Such systems are used, in particular, in Dubna and Obninsk.

In 2002, a simple planar system was proposed for irradiation of targets in any locations. The initially horizontal beam is turned in the vertical plane through a significant range of angles relative to the horizontal (for example, $-45° < f < 45°$), and the procedure table with the immobilized horizontally lying patient is moved in the vertical plane over the range (-1 m $< h < 1$ m) such that the beam hits the target [11]. This system can be placed within a room of size 4 × 5 × 6 m, is simple to use, has a maximum beam turn angle of 45° (a gantry with any beam direction can turn the beam through about 180°). However, it also uses vertical movement of the table with a horizontally immobile patient, so that it also cannot be used.

A compact and simple planar system with three fixed beam directions in the vertical plane (for example, –40°, 0°, 40°) and a common stationary irradiation center was proposed in 2016 for irradiation of any target location in an immobilized lying patient [14]. The range of beam directions was increased in this system using an additional small (up to ±15°) turning of the procedure table bearing the patient fixed relative to the horizontal axis passing through the center of the target parallel to the longitudinal axis of the patient. Here (as in every gantry [10]), it is useful to monitor body and target shape directly at the irradiation site using a horizontally moveable tomograph (see Fig. 2). In each fraction, after a single tomograph run, three independent directions of irradiation can be used with the patient in a fixed position. Thus, in the process of multifractional treatment with a maximum table rotation of up to ±15°, any beam direction in relation to the patient within the range ($-55° < F < 55°$) on both sides of the patient can be used. All the magnets in this apparatus are stationary and have a significantly smaller total weight (less than 10 t), power, and cost than the magnets of any gantry (full beam rotation in any gantry in any direction is about 180°), though actual calculations must be performed to link with a particular accelerator. This planar system can be located in a room of size about 8 × 5 × 4 m. The opportunities for irradiation in this system are comparable to those provided by a gantry.

In standard systems, transport of the beam to the gantry in the procedure room uses several quadrupole lenses in each straight section between rooms, while turning of the beam into each procedure room uses two magnets and several quadrupole lenses. The beam is then focused onto the target. Without a gantry, transport of the useful beam into the three procedure rooms uses a simplified compact transport scheme. Directing the beam into any of the rooms requires one magnet (see Fig. 3). Lenses placed before the magnet focus the beam into the center of the magnet, while lenses paced after the magnet focus the turned beam onto the target in the corresponding room. These lenses simultaneously suppress “linear beam dispersion” – deviation of particles with different energies from the main direction of irradiation of the beam axis arising when the beam turns in the magnet. Although this focusing does not eliminate “angular beam dispersal,” it has virtually no effect on the quality of beam focusing on the target. We note that this type of system can be used both sequentially and for turning the beam in the vertical plane. Thus, the system proposed here for transporting the proton beam useful for irradiation from the accelerator to the three procedure rooms uses fewer magnet elements, requires less power, and occupies less space in a one-storey building.

Analysis of the potentials for transportation of the useful proton beam into the three procedure rooms using new compact systems for changing irradiation beam direction in place of a gantry led to suggestion of a scheme in which the main equipment of the proton therapy center is positioned in a single-storey screened location with a minimum-size and minimum-cost beam transport system (see, for example, Fig. 3). This scheme can be used with any proton accelerator emitting beams useful for scanning targets [3].

Each of the rooms can be used either with a horizontal beam and a moving chair for treating targets in the head and neck or with any flat system. In all cases, all three rooms can operate without down time, independently, with extensive potentials for selecting the direction of irradiation, with monitoring of the volumic body and target shape using a tomograph at the irradiation site and with optimum active dose distribution through the volume of the target. In all cases, the cost of the screened location and the equipment placed within it for transport of the useful beam is about half that of a standard (three-storey!) irradiation center and provides the opportunity for significantly reducing the costs of high-quality proton treatment.

Conclusions

This review assesses the potential for creating multicabin proton irradiation centers without gantries for high-quality, large-scale treatment of any location with main equipment of small size and low cost in buildings using simplified systems for transporting the useful beam from the accelerator to the patients. This should decrease the cost of treatment and make proton beam therapy more accessible for patients.

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