Seminars in
RADIATION
ONCOLOGY

Can Technological Improvements Reduce the Cost of Proton Radiation Therapy?

Jacobus Maarten Schippers, PhD,* Anthony Lomax, PhD,*
Adriano Garonna, PhD,† and Katia Parodi, PhD‡

In recent years there has been increasing interest in the more extensive application of proton therapy in a clinical and preferably hospital-based environment. However, broader adoption of proton therapy has been hindered by the costs of treatment, which are still much higher than those in advanced photon therapy. This article presents an overview of on-going technical developments, which have a reduction of the capital investment or operational costs either as a major goal or as a potential outcome. Developments in instrumentation for proton therapy, such as gantries and accelerators, as well as facility layout and efficiency in treatment logistics will be discussed in this context. Some of these developments are indeed expected to reduce the costs. The examples will show, however, that a dramatic cost reduction of proton therapy is not expected in the near future. Although current developments will certainly contribute to a gradual decrease of the treatment costs in the coming years, many steps will still have to be made to achieve a much lower cost per treatment.
Semin Radiat Oncol 28:150-159 © 2018 Published by Elsevier Inc.

Introduction

In the initial phase of proton therapy, accelerator laboratories were the only places where it could be performed. In 1991, 41 years after the first treatment with a proton beam, the first hospital-based particle therapy facility[1] began operation. The facility was based on a synchrotron specially developed for proton therapy, together with the first rotating gantries. Since 2000, the number of clinical facilities in a hospital-based environment has increased steadily and, because of increasing interest by commercial companies during the last 10 years, more than 60 facilities are now in operation.[2] In addition, a clear shift out of the accelerator laboratories has taken place: currently more than 50. dedicated clinical facilities are linked to or are located at a hospital.

However, the major obstacle to broader adoption of proton therapy is the cost of treatment, which is still approximately a factor of 2-3 higher than the cost of technically advanced radiation therapy with photons. The major factor determining the cost differential is the capital investment needed for the equipment and the building. Other important contributions to the costs are the operation, the more intensive quality assurance procedures required for highly accurate proton dose delivery, and the less efficient patient throughput. Therefore, apart from a reduction in the investment costs, treatment costs can also be reduced by an efficiency increase in the treatment workflow. In this overview, current technological developments in these fields will be discussed in the context of their cost reduction potential.

In relation to current technological developments, the assumption is that smaller equipment will lead to smaller and thus less costly facilities. In parallel with this facility size reduction, novel technology is also aiming at further improving treatment quality.[3,4] Although the latter developments do not necessarily aim for a lower equipment cost, cost reduction could be a convenient spin-off.

The ultimate goal of facility size reduction is to reach a footprint similar to what is currently needed for photon treatment techniques. The research on equipment size reduction has led to 2 developments which are currently being implemented. In the first group of developments, the price reduction is achieved just by cheaper accelerators and beam delivery systems for the typical multiroom facility setups. Although the initial investment will still be quite large, the cost per treatment is aimed to be lower than achievable in older facilities. The second group of developments is aiming at

*Paul Scherrer Institut, Villigen, Switzerland.
†TERA Foundation, CERN, 1211 Genève, Switzerland.
‡Ludwig-Maximilians-Universität München, Munich, Germany.
Address reprint requests to J.M. Schippers, Paul Scherrer Institut, WBGA/C36, 5232 Villigen, Switzerland. E-mail: marco.schippers@psi.ch

https://doi.org/10.1016/j.semradonc.2017.11.007
1053-4296/

systems that are attractive to institutions seeking single-room solutions. Our overview will concentrate on the technologies that might play a role in a cost reduction of the facility as well as on methods to improve the efficiency of the patient handling and throughput. The stated quantities and dimensions in this article are just approximations to indicate the order of magnitude and should thus not be used explicitly. Developments in gantries and in accelerators will be discussed first, followed by possible improvements in patient handling and facility layout.

Beam Delivery Systems in a Gantry

Current developments in gantry design aim at a combination of size reduction, a simpler mechanical design and, in some projects, novel beam transport methods applying new technology. The application of imaging techniques in relation to the gantries is discussed in section "Technology to Improve the Efficiency of Patient Throughput."

Although the layout has developed considerably, the basic concept and specifications of the gantries have not changed much since the first gantries for proton therapy,[1] in which the methods to achieve the most important characteristics can already be recognized. These first gantries were of the "corkscrew design,"[5] which is characterized by a bending of the beam, which is performed in 2 perpendicular planes after each other (eg, 90º upwards followed by 270º sideways). This has resulted in a gantry radius of 6 m with a length of only 7 m. Most other gantries[6] have a magnet layout that bends the beam within a single so-called bending plane (eg, 45º up followed by 135º down) toward the patient.

Compared to gantries for photon treatment, proton gantries are very large. The main reason for this is the mass of the protons, which is over 1800 times the mass of the electrons, which are the particles used to produce clinical photon beams. Therefore, proton tracks will have a bending radius of ~1.5 m, which requires large magnets. This and the other most important parameters determining gantry size are shown schematically in Figure 1. The magnet layout is determined by the beam dynamics constraints to achieve the correct pencil beam characteristics at the patient (only PBS—pencil beam scanning—systems will be discussed here). One of these is the

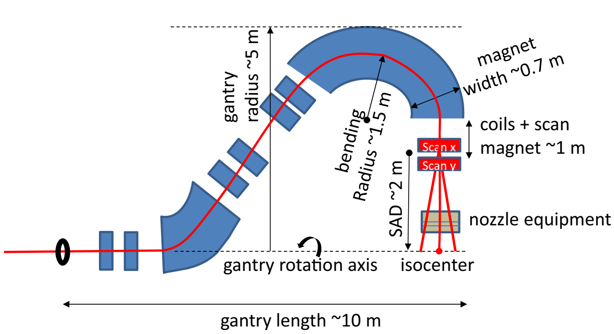

Figure 1 The most important parameters determining the total size of a gantry for proton therapy. (Color version of figure is available online.)

so-called achromaticity. In an achromatic gantry, protons within a range of 1%-2% energy spread (typical for most cyclotron facilities), will be guided through the gantry without losses and without affecting the pencil beam size and position at isocenter.

Usually the magnet layout is such that the beam is initially bent by 45°-60°, followed by bending 135°-120° in the opposite direction toward the isocenter. The latter bigger bending apparatus can consist of a set of magnets. The gantries can be made achromatic by using appropriate distances and the addition of several quadrupole magnets.

These and additional beam dynamics requirements strongly limit the possibilities to make a more compact gantry design. Present proton gantry designs typically have a length of 8-10 m and a radius of 4-5 m. As shown in Figure 1, in most gantries this radius is the sum of:

- 1.5 m for the bending radius of the proton beam,
- 0.5-1 m for the magnet widths of the bending magnets,
- 1 m for the space required for magnet coils and the scanning magnets, and
- 1.5-2.5 m for the source-to-axis-distance (SAD), the virtual source (location of scanning magnets) to axis distance, which is an important parameter to determine the maximum field size.

The typical nozzle equipment such as monitors etc., is located downstream of the scanning magnets, and thus within the SAD.

As can be seen in Figure 1, the most important contribution to the gantry radius is determined by the required SAD. A reduction of the SAD will lead to either complications due to the strong inclination of the pencil beams near the lateral edges of the field, or to a smaller field size to prevent this effect. However, one can also locate the scanning magnets before the last bending magnet (eg, at the Paul Scherrer Institute [PSI], Heidelberg Ion Therapy [HIT] facility, and the National Institute of Radiological Science [NIRS]),[7-11] or in between the last bending magnets, like in, for example, IBA's Proteus-ONE gantry.[12] In these "upstream scanning" layouts (Fig. 2), the space between the last bending magnet and the patient can be reduced significantly, since it is only required to accommodate nozzle equipment.

In the PSI, HIT, and NIRS gantries, the last bending magnet has been designed such that the scanning is performed as a parallel displacement of the pencil beam in the transverse plane at the isocenter. In this way, a very large or infinite SAD has been achieved with a gantry radius in the order of only 3.5 m.[8] A gantry radius of only 2 m has been achieved by also including an off-centered table, which is counter rotating with the gantry.[7] Due to the required beam optics for the parallel scanning, these upstream scanning gantries are longer than the gantries with down-stream scanning. It is important to realize, however, that parallel scanning has some advantages in field patching, treatment planning, and dosimetry-related quality assurance procedures. But, given that most of these types of gantries have been developed to test new scanning concepts, and that there is no experience yet with commercial versions of this gantry type, it is not yet clear if these advantages will have a very big effect on treatment cost reduction.