Technology Survey of the Particle Therapy Machine

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1. Introduction

The particle radiotherapy becomes one of the important tools for cancer therapy over the world. The advantage of the particle radiotherapy is its Bragg peak characteristics during interaction with the matter compared with the photon as shown in Figure 1 [1]. Not only the accelerator technology but also the clinical results push forward the advances in particle radiotherapy. There are two particles, proton and carbon, which are used widely in particle radiotherapy and there are total 121 machines operating in 2022, 88% is proton therapy machine and 12% carbon machine as shown in Figure 1 [2]. Also, there are 33 machines under construction including two carbon machine in Korea as shown in Figure 2, and 32 machines under planning including first carbon machine in USA [2].

It has been thought that the accelerator itself was a merely a part of the radiotherapy and reached its saturation with a view point of technology, but accelerator people have tried to develop new technology suitable to the radiotherapy machine to supply a more safe and comport environment for the patient. Recently, the Next Ion Medical Machine Study (NIMMS) is launched at CERN in order to leverage on CERN technology for a new generation of accelerators for cancer therapy with ion beams [3].

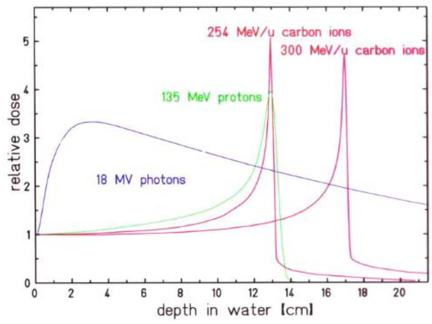

Fig. 1. Absorbed dose distribution depending on the radiation

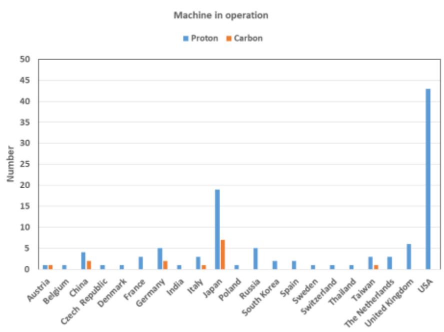

Fig. 2. Particle radiotherapy machine in operating in the world

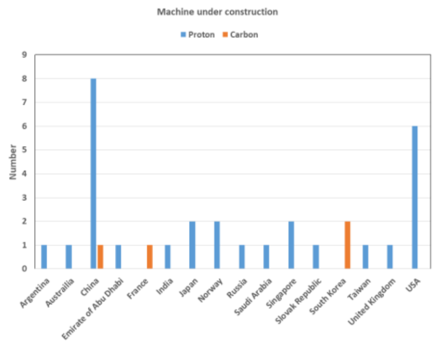

Fig. 3. Particle radiotherapy machine under construction in the world

2. Proton Radiotherapy Machine

The typical proton radiotherapy machine consists of a negative ion source, 230 MeV cyclotron, passive or active beam delivery system and gantry except the first proton machine dedicated to radiotherapy at Loma Linda University Medical Center, where 250 MeV synchrotron was used to accelerate the proton [1]. Recently, several companies are developing and delivering a proton radiotherapy machine including not only the accelerator itself but a beam delivery system, gantry, dose measurement and a treatment planning system for the clinic center. The beam delivery system changes from the passive system to the active system by using pencil beam which can eliminate the complex beam shaping devices such as a scatterer, ridge filter, bolus and so on [1]. Also, compared to the conventional multi-room proton system, a single room proton therapy machine delivering a pencil beam scanning combined with the dimensionally accurate imaging of 3D Cone Beam Computed Tomography (CBCT) enabling physicians to truly track where protons will be targeting tumor cells has been developed [4]. The superconducting synchrocyclotron has been developed for its small volume. This small size enables the concept of gantry – mounted cyclotron, which can dramatically reduce the required volume of the proton radiotherapy machine [5].

3. Heavy Ion Radiotherapy Machine

The number of the heavy ion radiotherapy machine under operation is about 14% of the number of proton machine [2]. The typical accelerator consists of an ion source, linear accelerator, synchrotron as shown in Table 1 [1]. The ion source should produce carbon ion beam with +4 charge state at least to increase the acceleration efficiency of the accelerator. A radio frequency quadrupole (RFQ) and a drift tube linac (DTL) are following to increase the beam energy suitable for injection to the synchrotron. Both the multi-turn injection and slow extraction technology are used in the radiotherapy synchrotron. The most technically difficult part of the carbon radiotherapy machine is the gantry. The magnetic rigidity of a proton with 230 MeV energy is 2.5 Tm, whereas that of a carbon with 430 MeV/u is 6.3 Tm [6]. This difference causes the weight of the carbon gantry with conventional warm magnet reach about 600 ton which is the much heavier and larger than the proton gantry. In the middle of 2010's, Toshiba developed the superconducting gantry for carbon radiotherapy machine, which was a half of its weight compared with the warm magnet gantry [7].

Table 1: Representative heavy ion radiotherapy machine

Facility	Accelerator
HIMAC (Chiba, Japan)	Ion source: ECR RFQ: 0.8 MeV/u DTL: 9 MeV/u Synchrotron: 800 MeV/u
PATRO (Hyogo, Japan)	Ion source: ECR RFQ: 1 MeV/u DTL: 5 MeV/u Synchrotron: 320 MeV/u
HIT (Heidelberg, Germany)	Ion source: ECR RFQ: 0.4 MeV/u IH-DTL: 7 MeV/u Synchrotron: 430 MeV/u
CNAO (PAVIA, Italy)	Ion source: ECR RFQ: 0.4 MeV/u IH-DTL: 7 MeV/u Synchrotron: 480 MeV/u

A synchrotron with superconducting magnets is suggested to reduce the accelerator size. It used superconducting magnets as the 90 degree bending magnet and its configuration could reduce the circumference to about 27 m, whereas the circumference of the synchrotron of the conventional warm magnet was about 75 m. A linear accelerator option is also suggested in order to reduce the foot print of the carbon radiotherapy machine. It uses an electron beam ion source (EBIS) as an ion source, 750 MHz RFQ and 3 GHz side coupled drift tube linac (SC-DTL). In order to reduce the foot print of the linac, a fold structure with the RF accelerating structure in the bending area was adopted. The folded linac length reached about 34 m with 430 MeV/u carbon energy.

3. Conclusions

The particle radiotherapy has advantage over the conventional photo radiotherapy in its Bragg peak characteristics and this promoted the proton and carbon therapy became popular around the world. Several technology developments have been studied to increase the adaptability considering not only the cost but the safety. A single room proton therapy and gantry-mounted cyclotron are proposed for the proton therapy, whereas an active scanning beam delivery system is widely adopted in the clinic centers. A superconducting gantry for carbon therapy is used nowadays, whereas a superconducting synchrotron and linac based carbon therapy machine are proposed in order to reduce the foot print of the machine.

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