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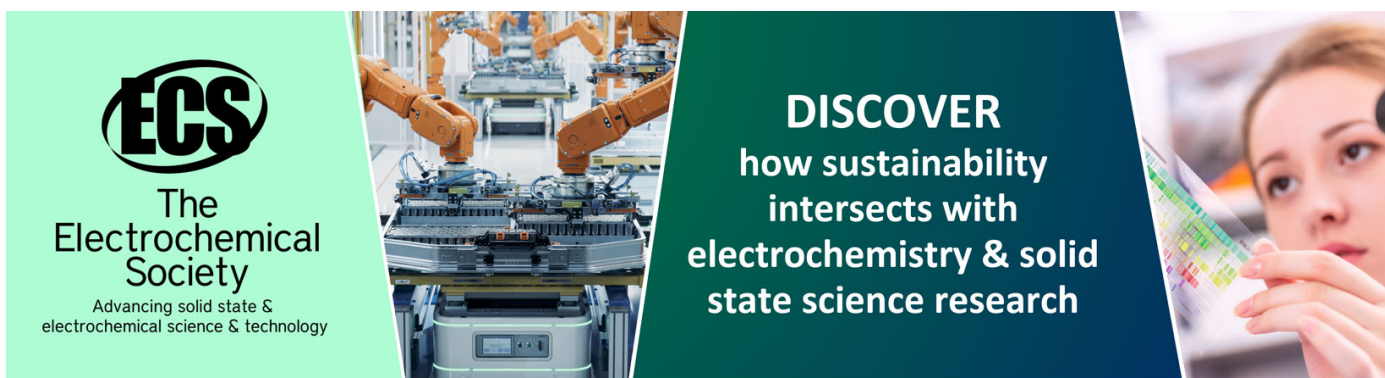
Progress of radiotherapy technology with HIMAC

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Progress of radiotherapy technology with HIMAC

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Abstract. NIRS has conducted a carbon-ion radiotherapy with HIMAC since 1994. For the progress of the carbon-ion radiotherapy technology, NIRS has developed beam-delivery technologies such as a broad-beam, a pencil-beam 3D-scanning and a superconducting rotating gantry. These technologies have been applied for both the static and moving tumor treatments. Further, NIRS just starts “Quantum Scalpel” project. In this project, a multi-ions irradiation for the LET-painting is studied to obtain the higher treatment efficacy. An ultra-compact heavy-ion radiotherapy machine, with much lower cost, has also been being developed by applying the superconducting and laser technologies for widespread use of the heavy-ion radiotherapy in the world.

1. Introduction

Heavy-ion (HI) beams are very suitable for deeply-seated cancer treatment not only owing to their high dose localization around the Bragg peak, but also owing to the high biological effect there [1]. NIRS, therefore, constructed HIMAC as the world’s first heavy-ion accelerator facility dedicated to medical use [2]. NIRS has conducted a carbon-ion radiotherapy (RT) with HIMAC since 1994, which results in accumulating the number of patient treated of more than 11,000. The carbon-ion RT has so far proven to be significantly effective against radio-resistivity tumours such as a bone cancer and a malignant melanoma, while keeping the quality of life without any serious side effects. It has also reduced the number of treatment fractions in treatments of common cancers, which leads to a shorter course treatment than the low LET RT. NIRS, thus, proposed a standard carbon-ion RT facility [3] to boost the carbon-ion RT in Japan, with emphasis being placed on a compact version so as to reduce a construction cost. As a result of the development, both the facility size and costs were to be around one-third compared with those of HIMAC. The fruits of this work were born in a pilot facility in the Gunma University that has been successfully conducted since 2010.

Since 2006, on the other hand, NIRS has been engaged in a “New Treatment Research Project” for further development of the HIMAC RT, such as the “adaptive cancer radiotherapy”. NIRS, thus, has developed a fast 3D scanning with a pencil beam. The new treatment research facility in order to verify the technology proposed through the clinical study was constructed. The first patient was treated in May 2011 in a fixed beam-delivery room. A compact carbon-ion rotating gantry with superconducting (SC) technology [4] has been utilized for static-tumor treatments since April 2018.

NIRS has just proposed a new development plan, which called it “Quantum Scalpel” project. Objectives of this project are to obtain a higher treatment efficacy of the HI RT and to realize an ultra-compact RT machine with much lower cost. As an LET-painting technique for controlling a biological effect considered the relative biological effectiveness (RBE) and the oxygen enhancement ratio (OER) on a tumor, the multi-ions irradiation scheme has been being studied [5]. For ultra-compact machine,



further, the quantum scalpel is to employ a laser-acceleration injector, a SC synchrotron and a SC rotating gantry.

This paper reviews the development and introduces a future plan of HIMAC.

2. Development of pencil-beam 3D scanning and rotating gantry

2.1. Pencil-beam 3D scanning

The pencil-beam 3D scanning is very suitable for the adaptive cancer RT, because this method requires neither the compensator nor patient collimators taking long manufacturing time. A pencil-beam 3D scanning is a beam delivery method to paint the dose distribution with a small beam and narrow Bragg peak. The pencil beam is laterally scanned (lateral scanning) to form a lateral dose distribution with orthogonal scanning dipole magnets and is then longitudinally scanned with a certain depth (slice) by either an energy absorber or by stepwise energy change from the accelerator.

2.1.1 Lateral scanning

Applying the pencil-beam 3D scanning to a moving-tumor treatment is difficult, because beam positions prescribed are moving. NIRS, therefore, has developed a phase-controlled rescanning (PCR) [6-8], based on the fast 3D scanning, for both the static and moving tumor treatments. The PCR method utilizes the fact that the tumor movement is close to “zero” on average during one respiration period. When a rescanning irradiation of one slice is completed within one respiratory-gated period, the PCR can obtain a uniform dose distribution even under irradiation of the moving tumors. The PCR method requires mainly two technologies: 1) Intensity-modulation technique for a constant irradiation time on each slice with a different cross section [9, 10] and 2) Fast 3D-scanning with pencil beam for completing several-times rescanning within a tolerable time [6].

2.1.2 Depth scanning

In the 3D scanning, the irradiated depth should be longitudinally changed, which called it depth scanning. In the first step, energy absorbers were used for the depth scanning. However, a variable-energy operation by accelerator itself has great advantages over that by the energy absorber; keeping the spot size small and suppressing secondary neutron yield. The multiple-energy operation, therefore, has been developed applying the extended flat-top operation of synchrotron. At first step of variable energy operation, an eleven-step energy operation from 430 to 140 MeV/n was developed [11, 12]. In this scheme, range of more than 3 cm is changed by the energy change with the synchrotron, while that of less than 3 cm by thin energy absorbers. As the second step, the 201-step energy operation, which can change the energy ranging from 430 to 56 MeV/n, has been developed [13]. The energy change in one step corresponds to a range shift of 2 mm.

2.2. Rotating gantry

A SC rotating gantry with the fast 3D-scanning, has been developed [2] for the more accurate and shorter-course treatment. The gantry is designed to deliver carbon-ions with the energy of up to 430 MeV/n to the iso-center with irradiation angles of over ± 180 degrees, and the maximum irradiation field of 20×20 cm². The SC rotating gantry consists of ten combined-function SC magnets, a scanner and two pairs of beam profile-monitors and steering magnets. The gantry length and the diameter are around 13 and 11 m, respectively. Since April 2018, the SC rotating gantry has been in practical use for a static-tumor treatment and been carried out as the clinical study for moving tumor.

3. Quantum scalpel project

NIRS has proposed the “Quantum Scalpel” project to obtain a higher treatment efficacy and to realize an ultra-compact RT machine with much lower cost for widespread use in the world.

3.1. Multi-ions irradiation

In the HIMAC treatment with a carbon-ion beam, a biological-dose distribution, described by (absorbed dose) $\times$ (RBE), has been delivered to be constant over a planning target volume (PTV), while the RBE and OER distributions have not yet been controlled. It is noted that the RBE increases with increasing the LET ($< \sim 200$ keV/ μ m) while the OER decreases with increasing the LET (~ 20 keV/ μ m $<$ LET $< \sim 200$ keV/ μ m). In this case, the LET distribution is shown in Figure 1 (a). This irradiation scheme gives the higher biological effect around the PTV boundary which is close to a normal tissue, because the Bragg-peak regions from various directions distributes around the PTV boundary. On the other hand, the lower one appears in the central region of the tumor. When a hypoxic state is in the central region of the tumor, a carbon-ion beam might not be effective due to highly resistivity against radiation. As one of the RBE-control methods, it was proposed that the RBE can be uniformly distributed across the PTV with two opposed carbon-ion fields [14]. NIRS has proposed the multi-ions irradiation to control the biological effect over the PTV. As shown in Figure 2 (b), the central region of the PTV is covered with the higher biological effect by mainly oxygen-ion, the PTV boundary with the lower one with mainly the helium-ion and the other region with middle one by mainly carbon-ion. It is noted that one can obtain a uniform biological-dose distribution even in this case. Combining a rotating gantry with 3D scanning, a multi-ions RT with the IMPT [15] will bring much higher treatment efficacy.

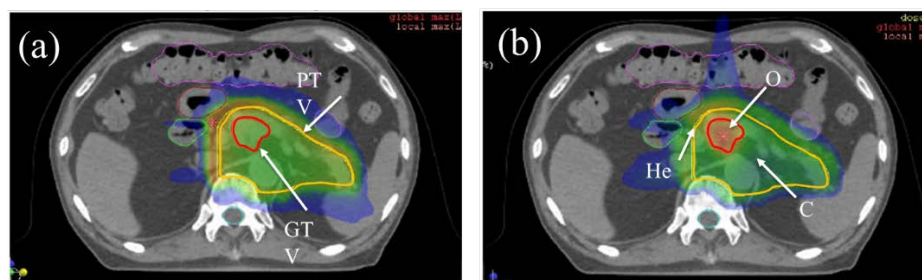


Figure 1. LET distribution, (a) with only carbon-ion, (b) with helium, carbon and oxygen-ions.

3.2. Ultra-compact HI RT machine

NIRS has studied a conceptual design of an ultra-compact HI-RT machine with the superconducting and laser technologies. The size of the machine is 10 m $\times$ 20 m, corresponding to two photon RT rooms. This machine consists of a laser-acceleration injector with 4 MeV/u, a SC synchrotron ring with around 7 m in diameter and a SC rotating gantry. In a conceptual design, the SC synchrotron can accelerate ions from 56 to 430 MeV/u with an injection energy of 4 MeV/u. The dipole field of the main magnet is designed to be 4 T at maximum and the field-change rate of around 1 T/s. The SC rotating gantry can be significantly downsized by a higher magnetic field of around 5 T and a compact scanner. As a result of a beam test of the compact scanner, the irradiation field size of 24 cm $\times$ 24 cm in 3.5 m of the distance from the entrance of the scanner to the iso-center, while the present scanner requires 9 m to obtain the same field size. A layout of the quantum scalpel is shown in Figure 2.

4. Summary

Almost 1 million and 14 million persons are diagnosed with cancer every year in Japan and in the world, respectively. In such a situation, NIRS has progressed the carbon-ion RT technologies. NIRS developed especially a standard carbon-ion RT facility in Japan, which bore fruit in a pilot facility in Gunma University. Following on from the pilot facility, three additional facilities have been successfully conducted and one facility has been being constructed in Japan. After ten years, further, it is forecast that the cancer patient number will continue to rise to 22 million persons every year in the world. Therefore, NIRS starts the “Quantum Scalpel” project, which will have a higher treatment efficacy with much lower cost to boost the heavy-ions RT in the world.

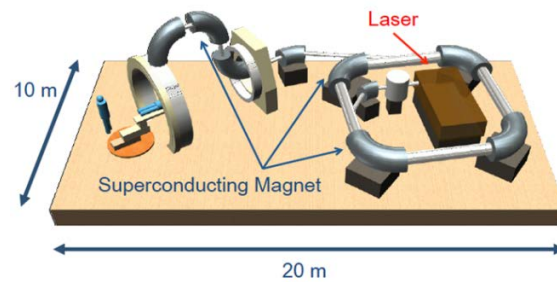


Figure 2. Layout of Quantum scalpel.

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