RADIATION ONCOLOGICAL FACILITIES OF THE HIMAC

Kiyomitsu KAWACHI, Tatsuaki KANAI, Masahiro ENDO, Yasuo HIRAO and Hiroshi TSUNEMOTO

Abstract The project to construct a Heavy Ion Medical Accelerator in Chiba (HIMAC) started at NIRS in 1984, and the final design studies, including the buildings, have already been completed based upon radiation oncological requirements. HIMAC comprises two ion sources, an RFQ linac, an Alvarez linac, a synchrotron, a high-energy beam transport system, and radiation oncological facilities. The main accelerator synchrotron consists of double rings operated at a repetition rate of 0.5 Hz, with a phase difference of one half period. The required ion species lie between helium and argon in order of atomic number. The output energy varies from 100 to 800 MeV/u for ions with a charge-to-mass ratio of 1/2. Radiation oncological facilities include all of the treatment and paramedical facilities as well as experimental facilities for radiation oncology physics and biology. The sophisticated treatment facilities consist of a beam delivery system, a patient positioning system, and a treatment planning system. These systems comprise all of the devices necessary for three-dimensionally conformed irradiation which is required for heavy-ion treatment. The entire HIMAC facility will be completed in 1993.

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Key words: Heavy ion, Medical accelerator, Particle therapy, HIMAC

INTRODUCTION

Cancer control is one of the most important challenges facing the Japanese. The government put into operation a "Comprehensive 10-year Strategy for Cancer Control" in 1984. Since then, the National Institute of Radiological Sciences (NIRS) has been promoting a project for the construction of a Heavy Ion Medical Accelerator in Chiba (HIMAC) based on the above strategy for cancer control. Radiation oncology has played an important role in cancer treatment, especially with regard to the conservation of organs and their functions. However, patients have not always been satisfactorily treated by conventional radiation (such as X-ray or cobalt gamma-rays) because of poor dose localization and the existence of radio-resistant tumors.

During the last thirteen years, NIRS has carried out clinical trials involving fast neutrons and protons in place of the commonly used types of radiation for far advanced and highly incurable cancers. Some of the results have indicated significant improvements in the local control rate for tumors involving selected organs\(^{1,2}\). These cases are closely related to the excellent physical dose distribution of protons and higher biological effectiveness of neutrons. Furthermore, based on the prospective results of heavy-ion research work at Lawrence Berkeley Laboratory (LBL)\(^3\) and recent progress in accelerator technology, we believe that heavy-ion beams will become significantly superior to the most effectively used conventional radiation.

HIMAC is the first heavy-ion accelerator dedicated to medicine in the world, and its design is based on the radiation oncological requirements below. This paper is mainly...
concerned with the current situation and future technological developments at the HIMAC radiation oncological facilities.

**RADIATION ONCOLOGICAL REQUIREMENTS**

Radiation oncological requirements were the basic factors that determined the HIMAC design; required ion species were chosen as a result of basic research on relative biological effectiveness (RBE) and of clinical trials at LBL. The RBE value increases from 1.0 at low LET levels of less than 10 keV/μ, to a maximum value of about 3.0 at LET levels of 140 to 160 keV/μ; it then decreases rapidly at higher LET. The LET ranges of the various ions depend on the ion species and their energies; at higher energies, ions generally have lower LET values. The LET values of ions increase with a decrease in the energy and have their highest values just before the end of the range. As a result of these features, the most biologically and clinically desirable ions exist in the atomic number range between 2 (helium) and 18 (argon).

The maximum required range in-tissue of ions was determined from clinical experience involving conventional radiation therapy at NIRS; range of 30 cm in soft-tissue is sufficient to cover deep-seated tumor therapy. The requirement for silicon—expected to be the most suitable and the heaviest ion for the deep seated and radio-resistant tumor therapy—has determined the maximum energy of this facility. As shown in Fig. 1, the maximum energy for silicon, which has a charge-to-mass ratio of 1/2, should be 800 MeV/u; for ions lighter than silicon, the 800 MeV/u capability may provide range in-tissue considerably greater than 30 cm.

The minimum energy was chosen in terms of the treatment of tumors in shallower regions using helium ions. Even if an energy degrader is used, the energy must be less than 100 MeV/u, which is equivalent to a range of about 8 cm in soft-tissue for helium. The range at this energy level for heavier ions will be considerably shorter than 8 cm in tissue.

The dose rate requirement for any ion beam is 5 Gy/min to permit completion of the treatment of one fraction within one minute. Presently, however, it seems to be rather difficult to realize the required dose rate for all ions, especially in the case of the heavier ions such as silicon and argon. Therefore, based on a careful investigation of accelerator technology and a compromise with clinical requirements, guaranteed dose rate values for every ion species have been reduced from the values above.

The maximum treatment field size of the beam was also selected based on clinical experience at NIRS; most treatments are satisfactory with a maximum field size 22 cm in diameter.

The capability to employ both vertical and horizontal beams is essential for heavy-ion treatment with a highly-controlled dose.
distribution. The radiation oncological requirements are summarized in Table 1.

**ACCELERATOR DESCRIPTION**

1. **Accelerator Specifications**

In order to choose an appropriate accelerator system, the most fundamental criteria are the accelerating ion species and the energy range; and they are derived from the radiation oncological requirements above.

To satisfy these requirements, a synchrotron is the most suitable choice for the main accelerator of this facility. However, since a synchrotron only provides a pulsed beam with a period of a few seconds, it is necessary to prescribe that the beam waveform have a long and flat top beam intensity in one pulse for precise control of the delivered dose. These specifications are listed in Table 2 as duty factor and repetition rate.

The beam intensities for various ion species to be extracted from the synchrotron ring were estimated from the guaranteed dose rates. Since it seems to be rather difficult to achieve the required dose rate (5Gy/min) for any one ion species, the guaranteed dose rates were determined from the present technological level of ion sources and beam delivery for treatment. The values for various ions are listed in Table 3; however, the beam intensity values might be somewhat higher than the critical value.

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**Table 2. Accelerator Specifications**

<table>
<thead>
<tr>
<th>Ion Species</th>
<th>Maximum Energy (for ε=0.5)</th>
<th>Minimum Energy (for ε=0.5)</th>
<th>Beam Intensity (for C)</th>
<th>Duty factor</th>
<th>Repetition Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>He to Ar</td>
<td>800 MeV/u</td>
<td>100 MeV/u</td>
<td>2.0 × 10⁹ pps/ring</td>
<td>20% /ring</td>
<td>0.5 Hz /ring</td>
</tr>
</tbody>
</table>

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**Table 3. Guaranteed dose rates at a target of 1/ and extracted synchrotron beam intensities (flux) for various ion species.**

<table>
<thead>
<tr>
<th>Ion species</th>
<th>Dose rate (Gy/min)</th>
<th>Extracted flux (pps/ring)</th>
</tr>
</thead>
<tbody>
<tr>
<td>⁴He</td>
<td>5</td>
<td>1.2 × 10¹⁰</td>
</tr>
<tr>
<td>¹²C</td>
<td>5</td>
<td>2.0 × 10⁹</td>
</tr>
<tr>
<td>²⁰Ne</td>
<td>2</td>
<td>3.4 × 10⁸</td>
</tr>
<tr>
<td>²⁸Si</td>
<td>0.5</td>
<td>4.5 × 10⁷</td>
</tr>
<tr>
<td>⁴⁰Ar</td>
<td>0.5</td>
<td>2.7 × 10⁷</td>
</tr>
</tbody>
</table>

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Fig.2. A cross sectional bird's-eye view of HIMAC.
This is because consideration of RBE values for high LET heavy-ion beams was neglected and an over estimate occurred in the uncertainty of the beam loss caused by beam spreading and field shaping for irradiation.

The most suitable accelerator complex for the facility was determined by taking into account these specifications and currently existing reliable accelerator technology as well cost performance. Fig.2 shows a cross-sectional bird's-eye view of the total layout of the HIMAC facility. It consists of two types of ion sources, two types of linacs, double synchrotron rings, high-energy beam transport lines, and radiation oncological facilities for treatment and experiments.

2. Injector System

A view of the proposed layout of the injector system is shown in Fig.3.

The kinds of ion sources are a PIG (Penning Ion Guage) type ion source and an ECR (Electron Cyclotron Resonance) type ion source. The latter is suitable for rather heavier ions, such as neon, silicon and argon, and the former is suitable for lighter ions, such as helium, carbon and neon. The extracted beam only contains ions (selected by an analyzing magnet) with a charge-to-mass ratio between 1/7 and 1/4. These ions are further accelerated at DC accelerating gaps and focussed by solenoid and electrostatic quadrupole lenses. These heavy ions are then injected at 8-keV/u energy level into a Radio Frequency Quadrupole (RFQ) linac with a total length of 7.3m and a cavity diameter of 0.6m. Recently, the RFQ linac has been recognized as being the most suitable preinjector linac at low-velocity levels, and has been directly matched with the injector linac described below. The output energy of the RFQ linac is 800 keV/u.

The ions accelerated by the RFQ linac are fed into an Alvarez linac which is the most suitable injector for the low duty-factor synchrotron. The Alvarez linac is separated into three cavities with a diameter of about 2.2m and a total length of about 24m. The Alvarez linac has more than 100 drift tubes in the cavities: each tube is supported by horizontal and vertical stems, and is equipped with a quadrupole magnet for beam focusing. The operating frequency of the Alvarez linac is 100 MHz, the same as that of the RFQ linac. Ions are accelerated to 6 MeV/u by the Alvarez linac (and passed through carbon foil) so as to obtain a sufficient fraction of fully-stripped ions for any required ion species. Only fully-stripped ions will be injected into the following main accelerator; other ion beams will be fed into a medium-energy beam irradiation room for low-energy heavy-ion experiments.

![Fig.3. A plan view of the layout of injector system.](image-url)
3. Main Accelerator

The main accelerator comprises a pair of separated-function type synchrotron rings in order to easily provide a higher beam intensity and repetition rate. The two superposed synchrotron rings comprise of identical components and are separated by a shielding floor. A plan view of the upper synchrotron ring layout is shown in Fig.4. The average diameter of the ring is about 41m, and the circumference is about 130 m. The main components and performance of both rings have identical specifications; however, the difference between the lower and upper rings is that the latter has a fast extraction system, and the former has another injection system for the fast extracted beam. Both systems and the junction beam line have been planned to accommodate the future extensions.

The injection energy to the synchrotron rings is 6 MeV/u, and the output energy is continuously variable from 100 to 800 MeV/u for ions with a charge-to-mass ratio of 1/2. This is very important for reducing low-LET secondary particles (produced by fragmentation) and will be able to conform the best dose distribution to a target using the most appropriate heavy ions. Both synchrotron rings operate with a repetition

Fig.4. A plan view of the layout of upper synchrotron ring.
rate of 0.5Hz, and with a phase difference of one half period; this feature will greatly contribute to the reduction of the reactive power fluctuation rate.

4. High-Energy Beam Transport System

The accelerator system and all irradiation ports are connected by a high-energy beam transport system. Layouts of the high-energy beam transport lines are shown in Fig.5 and 6. Each beam extracted from the upper or lower ring will be dedicated to a horizontal or a vertical beam line, respectively. The horizontal lines provide horizontal beams to two treatment rooms (B and C), physical or general irradiation rooms, and a secondary beam irradiation room; however, on special occasions, the horizontal beam can be joined to the vertical line. The vertical lines provide vertical beams to two treatment rooms (A and B) and horizontal beams to a biological irradiation room. The vertical beam lines are quite large-scale elements in this system and they represent one of the most desirable radiation oncological features.

In these beam lines, a doubly achromatic feature is required to beam transport elements upstream of the switching area so as to effect fast beam switching from one room to another.

RADIATION ONCOLOGICAL FACILITIES

1. Radiation Oncology area

Radiation oncological facilities include all necessary treatment and paramedical facilities, as well as experimental irradiation facilities for radiation oncology physics and biology.

The main HIMAC radiation oncology areas are in the second basement of the HIMAC building. There are three heavy-ion treatment rooms (A, B, and C shown in Fig. 5), a main control room for treatment, a machine shop for radioactive materials, a treatment room for patient care and a waiting room. In room A the patients can only be treated with a vertical beam, as shown in Fig.6. In the HIMAC facility, the vertical

Fig.5. A plan view of the layout of horizontal high-energy beam transport lines.
and the horizontal beams can be simultaneously focused at the same point or at two different points. Therefore, in room B one beam enters the target area horizontally and the other enters vertically from above. In room C patients can only be treated with a horizontal beam.

The main control room for treatment is utilized for communication with the HIMAC control center concerning a patient’s treatment scheduling, alterations, and instructions regarding the treatment order taking place in each room. The machine shop for radioactive materials is utilized for the adjustment of beam modifiers (i.e. a compensator and collimator) that have been used once for each patient.

In the mezzanine of the second basement, there is an X-ray CT room (for treatment planning) and a simulation room used for verification of the suitability of a proposed treatment before actually admitting a patient to a treatment room.

The other radiation oncology areas are on the first floor: there is a patient reception room, a few examination rooms, a machine shop, a treatment planning room, and a prescription room. Beam modifiers and immobilization devices based on treatment plans, will be constructed for individual patients in the machine shop. In the treatment planning room, there is a large treatment planning computer and several treatment planning terminals. The prescription room is provided for assembling medical and technical staff, and reviewing individual cases.

2. Heavy ion treatment facilities

The HIMAC treatment facilities consist of a beam delivery system, a patient’s positioning system, and a treatment planning system.

The beam delivery system comprises several devices such as a scatterer changer, a pair of scanning magnets, a range shifter, a ridge filter, a multileaf collimator and several beam monitoring devices. The layout of typical beam delivery system in treatment room B is shown in Fig.7. A scatterer changer is a system which changes the scatterer according to the ion species, the energy and the required field size. A pair of scanning magnets are orthogonal bending magnets which can control wobbler scanning, raster scanning, or spot scanning, according to the use of suitable power supplies. A range shifter is a device which uses absorbers to fine tune the ion range to conform to the

Fig.6. An elevation of the layout of vertical high-energy beam transport lines.
maximum depth of the tumor: the absorber thickness is computer controlled. A ridge filter is a device used to select the most suitable filter for spreading the narrow Bragg peak according to the thickness of the tumor. A multileaf collimator is a computer-controlled field-shaping device which tailors the beam according to the perpendicular cross section of the tumor.

The patient positioning system consists of a laser pointer, a digital X-ray TV, a X-ray CT, a treatment couch, a compensator holder and patient immobilization aids. The laser pointer is an indicator of the beam center for heavy-ion treatment; the digital X-ray TV is used for beam definition and verification of the target volume setting position; and the X-ray CT is required to verify this setting position with respect to the field size and the depth at each slice of the patient. The treatment couch will be automatically controlled by the patient positioning computer linked to image verification devices. The design of the patient immobilization aids is incomplete but will be based on the requirements of radiation oncology staff. Some of these devices will be tested in proton therapy at NIRS before being applied to heavy-ion therapy. A beam modifier, such as a compensator and a patient collimator, will be designed and made for individual patients with the help of a treatment planning computer and a numerically controlled (NC) machine.

Patients referred to HIMAC will be pre-examined by conventional diagnostic procedures (at the very least). However, additional investigations, such as digital X-ray, X-ray CT, PET, MRI, radioactive beam implantation, and heavy-iron imaging, will be performed for the precise heavy-ion treatment. The diagnostic image data should be compatible with the computer software of the treatment planning system since the computer system uses it to determine the optimal heavy-ion therapy. Another main activity of the treatment planning system is iso-effect dose distribution simulation: this is based

Fig.7. A typical layout of the beam delivering devices for treatment room B.
on anatomical data obtained by the digital imaging methods above and dose distribution calculations taking into account inhomogeneous electron density and biological response factors in the body. The treatment planning computer is also capable of designing a compensator and a collimator for each patient, as well as running an NC machine. These activities—now under development—are all included in the design of the treatment planning system.

3. Experimental irradiation facilities

A physics or general irradiation room is provided not only for experiments related to radiation oncology physics, but also for fundamental experiments in physics and other fields. The secondary beam irradiation room is provided for the development of diagnostic and therapeutic applications of radioactive beams and for fundamental data acquisitions of the secondary beams. The biology laboratory is provided for small and intermediate animals, for tissue-cultured cells, and for the use of a small amount of radioactive materials. The irradiation facility is almost the same as the beam delivery system for the treatment rooms, except for a multileaf collimator. This multidisciplinary, multi-user research facility will provide a unique opportunity and a new horizon for the radiation oncology.

DISCUSSION

The radiation oncological requirements for heavy-ion research work not only include clinical trials of heavy-ion beams, but also fundamental research work such as medical physics, radiation biology, and radiation chemistry. Therefore, it is very important that the HIMAC radiation oncological facilities are flexible enough to allow for the different eventualities possible in future extensions.

Firstly, if it is possible to produce radioactive beams of an intensity sufficient for treatment as well as diagnosis, these beams will be produced just before the junction of the horizontal and vertical beam lines. In this case, the junction line will be used for analyzing the section of secondary beams, and the selected radioactive beams will be provided as vertical treatment beams. This feature is very important for radiation oncology since it becomes possible to easily and precisely verify an irradiated area with treatment beams.

Secondly, since effective and sophisticated use of double synchrotron rings is based on technological improvements, the following features can be expected:

(1) Simultaneous irradiation with horizontal and vertical beams in treatment room B.

(2) Two beams may be used simultaneously in different treatment rooms or experimental irradiation rooms.

(3) In case of trouble involving one synchrotron ring or in limited parts of the high-energy beam transport lines, the beam-failure probability will be reduced to some degree by joining the upper and the lower beam lines.

As a future extension of the facility, if the junction beam line between two rings (a fast extracted beam from the upper ring injected to the lower ring) is completed, the following feature can be expected:

(4) Two-stage cascade acceleration for ions heavier than argon by adding a stripper foil to the extended beam line.

It might be possible to use the lower ring as a storage ring following the upper synchrotron ring. In this case, the following features can be expected:

(5) Radioactive beams accumulated in the lower ring to provide treatment as horizontal or vertical beams.

(6) Patients may be treated for a very short time with a single shot of the accumulated stable heavy-ion beams.

Thirdly, a sophisticated beam delivery system to achieve three-dimensionally conformed (3D) irradiation, has been designed at this facility. The 3D irradiation feature is essential at this facility to prove the contention that heavy-ion therapy can be markedly
better than the best use of other conventional radiation therapies. The beam delivering system comprises a pair of scanning magnets and a multileaf collimator to automatically tailor the size and shape of the radiation field to the target shape at each depth in a patient's body. The most fundamental 3D irradiation procedure using the beam delivery system above and the compensator for each patient, has reported on previously\(^5\).

Further sophisticated 3D irradiation featuring the spot beam scanning method will also be possible with the utilization of a range shifter unit and upgraded power supplies for the scanning magnets. The procedure has been verified with the proton beams from the cyclotron\(^6\).

The 3D irradiation treatment not only requires the sophisticated beam delivery system, but also a sophisticated 3D treatment planning program taking into account both physical dose distribution and biological effects. Although the 3D treatment planning program is under development, its final completion will be considerably delayed after the start of HIMAC operation in order to compile the essential data.

**ACKNOWLEDGEMENT**

The radiation oncological requirements resulted from a series of discussions with many members of the physics, biology, medical and accelerator communities of NIRS as well as other universities and institutions. The design of the HIMAC facility has been realized as a result of the efforts of many members of the NIRS Division of Accelerator Research, Mitsubishi Electric Co., Sumitomo Heavy Industries, Ltd., Hitachi Ltd., Toshiba Corp. and Nikken Sekkei Ltd. Their contributions to this project have been very great, and we take pleasure in acknowledging the important part played by them.

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**REFERENCES**

要旨：重粒子線がん治療装置（HIMAC）の建設計画は1984年より放医研で開始された。HIMAC及びその建屋の詳細設計は、放射線腫瘍学の要求を基に、既に完成している。HIMACは2台のイオン源、RFQ線形加速器、アルベ型線形加速器、シンクロトロン、高エネルギービーム輸送系及び放射線腫瘍学施設から構成される。主加速器シンクロトロンは2つのリングで構成され、それぞれ繰り返し率0.5Hzで、互いに半周期位相をずらして運転される。本装置に要求されている粒子種は、原子番号でヘリウムとアルゴンの間の粒子であり、その出力エネルギーは荷電質量比が1/2のものに対して、核子当り100MeVから800MeVまで得られる。放射線腫瘍学施設は、重粒子線の治療と医療関連施設、放射線腫瘍物理学及び生物学の実験施設を含んでいる。特に洗練された治療施設はビーム照射系、患者位置決め系及び治療計画系等で構成されて、重粒子線治療では欠かすことのできない、3次元原体照射に必要な全ての機能を備えている。HIMAC施設全体は1993年に完成の予定である。