FUTURE MEDICAL ACCELERATOR

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Abstract

In the future radiation/particle therapy, the 3D-methods would be expanded into 4D- and 5D-methods to achieve precise biological dose focused on tumor cells and to spare normal cells as much as possible. No further technologies would be required to develop the next accelerator for radiation/particle therapy except for accelerator- and hospital- based BNCT. The BNCT needs a "medical neutron accelerator" to produce high intensity epithermal neutrons.

INTRODUCTION

The adjective word "Medical" is considered to have many meanings; precise, safe, stable, reliable, established, and so forth. These explanation would never be found in our dictionary. In development of "medical equipment" like a medical accelerator, however, these implicit meanings become very important basic concepts. Accelerator, medical, and co-medical specialists have to have these common concepts in our communication.

Since the discovery of accelerator in 1920's, the medical accelerator has been evolving into powerful equipment as a probe for radiation diagnostics and as a knife for radiation/particle therapy. At present, various kinds of medical application have been achieved in the fields of radionuclide production for PET and SPECT, radiation and particle therapy using X-ray, γ-ray, electron, proton and heavy ion particles produced by mainly RFQ and DTL linac, cyclotron, and synchrotron accelerators.

ACCELERATOR-BASED THERAPY

Figure 1 shows a top view of proton therapy facility at PMRC [1], where setup (A) RFQ and DTL linac, (B) proton synchrotron, (C) high energy beam transport, (D) rotating gantries, and (E) patient beds in (E) treatment rooms. The proton therapy facility needs a large space (ex. 40mx40m for PMRC) for setting up these equipments and another large space for peripherals; power supplies, control system, and so forth.

Radiation/Particle Therapy

In the radiation/particle therapy, the important things are precise exposure of radiation. Starting with a technically-easy-and-safe passive-3D method using compensator/aperture or wobbler magnets, radiation/particle therapy has been evolving into passive 3.1D using respiration gate system, dynamic 3D using raster or spot scanning system and dynamic 3.1D using the scanning system with respiration gate system. The dynamic 3.1D requires high speed painting technique at several dozens of Hz or more to prevent dose distribution from getting worse due to motion effects. The passive 3D method has evolved into multi-layered conformal therapy using multi-layered SOBP filter [2] in particle therapy to improve dose distribution more conformal. In another way of dynamic 3D method, the intensity modulated radiation therapy (IMRT) has been developed in the radiation therapy to spare normal tissue and to concentrate radiation into a tumor part. In the particle therapy, a similar method called IMPT has been proposed as well.

Figure 1: Proton therapy facility at PMRC. A: RFQ and DTL linac, B: proton synchrotron, C: high energy beam transport, D: rotating gantries, E: treatment rooms, F: patient beds.

Boron Neutron Capture Therapy (BNCT)

In the last decade, the Boron Neutron Capture Therapy (BNCT) has been highlighted again as one of the particle therapy available to cure invasive cancer and widely-spread cancer, in which tumor cells are mixed into normal

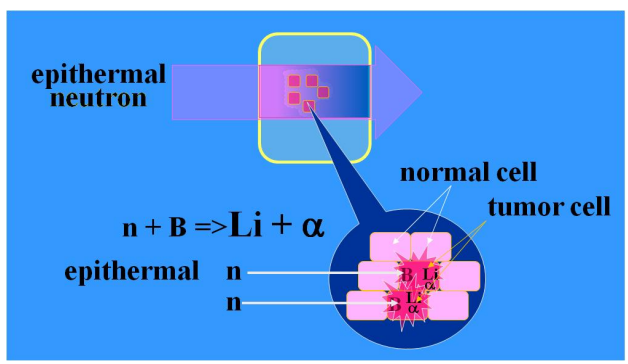

Figure 2: Principle of BNCT.

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tissues at cell level. Since neutrons have a power to produce tumor-cell-selectively-damageable particles, α and Li particles, in a cell in reaction with ^{10}B atoms concentrated into only tumor cells, the BNCT is much brighter therapy for their refractory cancers. Fig. 2 shows a principle of BNCT. Incident epithermal (0.1eV–10keV) neutrons reduce their energy in the passage and become thermal (10-100 meV) neutrons in a patient. Protons interacted with the epithermal and thermal neutrons deposit energy into the passage (pink area) in a human body (yellow area), where the normal cells and tumor cells exist. In the radiation/particle therapy, the energy is deposited into all cells in the target. In the BNCT, however, only the tumor cells including ^{10}B compounds are selectively enhanced in dose (dark pink area) because of the nuclear reaction, ^{10}B(n,α)^{7}Li, where the production particles α and ^{7}Li stop inside the cell and deposit all the energy into the cell only. The ^{10}B compounds are injected into a patient just before neutron exposure. Normal cells around the tumor cells are spared.

Neutron source was only a nuclear reactor. In these days, the new accelerator technology has made it feasible to produce high intensity neutrons. Recently the neutron source has been switching from the nuclear reactor to the accelerator, which can control neutron beam intensity and switch on/off easily. The accelerator-based BNCT became considerable as a realistic proposal at a hospital. In this accelerator-based BNCT, neutrons are secondary particles produced in the reaction of primary protons on Li or Be target. It takes about 60 minutes to complete irradiation for a patient in use of 10mA proton accelerator at 8-MeV in BNCT. Currently no fractional irradiation is performed to prevent a patient from feeling often unpleasant experience of injecting ^{10}B compounds. High intense of proton beams would make Li or Be target damaged due to heating-up. The important requirement in the hospital-based BNCT is such that no dangerous materials are produced and no radio activities are remained on the beam line. A high current of 10mA at 8MeV proton beam is currently one of the considerable beam conditions to produce 2x10^{9} neutrons/sec without much radioactive contamination unless some new ideas are proposed to the targets.

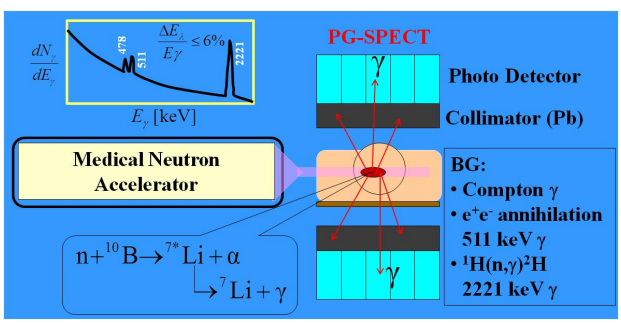

Figure 3: Principle of PG-SPECT.

Concentration of ^{10}B compounds fades out during treatment. The concentration is monitored with a prompt γ-ray SPECT (PG-SPECT) system. Fig. 3 shows an example of photon detection system in PG-SPECT. Epithermal neutrons produced by the medical neutron accelerator are interacted with ^{10}B in tumor cells. The reaction $^{10}\mathrm{B}(\mathrm{n},\alpha)^{7*}\mathrm{Li}$ are followed by the prompt decay process $^{7*}\mathrm{Li}\rightarrow\mathrm{Li}+\gamma$, in which the prompt γ-ray has an energy of 478 keV. The considerable backgrounds are the γ-rays produced in the reaction of Compton scattering (continuous energy), $e^{+}e^{-}$ annihilation (511 keV), and $^{1}\mathrm{H}(\mathrm{n},\gamma)^{2}\mathrm{H}$ (2221 keV). Since the 511 keV γ-ray is very close to the signal γ-ray of 478 keV, the energy resolution of the photon detector should be better than 6% at the signal energy. Dominant background is Compton γ-rays, which rate is an order of 10^{5}Hz. The collimator made of lead reduce the high rate to the order of thousand at the detector. One of the considerable γ detector candidate is the detector using a crystal sintillator viewed by a position sensitive photomultiplier tube (ps-PMT). The crystal LaBr3 has the currently best energy resolution of 4%. The response time is an order of ns, which is much faster than gas detector's response time.

The medical neutron accelerator consists of a high intensity proton accelerator and a neutron production target followed by a moderator to epithermalise the neutrons. Specification for the part of the proton accelerator is shown in Table1. The proton current is 10mA and the proton power on the target is 80 kW at maximum. The proton energy is selected to 8 MeV, which results in low radio activation in the treatment area.

Table 1: Specification of the part of the proton accelerator in the Medical Neutron Accelerator at PMRC

TYPE	RFQ+DTL PROTON LINAC	
Proton Energy	8 MeV	low activation
Peak Current	50 mA	same spec. as J-PARC
Averaged Current	>5 mA (10mA@max)	optimized thermal design of acc. tube
Repetition Frequency	>100 Hz (=>200Hz)	optimized thermal design of acc. tube
Power onto Target	>40kW (80kW@max)	optimized thermal design of target
Length, Area	<7m , <50m^{2}	

Comparison of the neutron production target is shown in Table2. Three types of targets are considered to produce high intensity neutrons. A solid Be target has advantages of high melting point 1,287 degrees, less radio activation, stable and easy handling. However, 8 MeV protons produce high energy neutrons, which have possibility to activate materials around. A solid Li target has advantages of low beam energy 2.5 MeV of protons. However, the Li target has disadvantage of producing radioactive ^{7}Be, which causes 20 mSv/h in a treatment

room when operating for 500 hours in a year. Another disadvantage is low melting point 180 degrees, which could cause melting target unless temperature is controlled absolutely stable. It could be dangerous in the treatment room. A liquid Li target has advantage of no target damage and has a disadvantage of explosive if mixed with water. It could be much dangerous as well.

Table 2: Comparison of Neutron Production Target

Material		Advantage	Disadvantage
Be	solid	●8 MeV protons => less activation ●High melting point 1287℃ ●Easy handling ●Stable	●Need remove high temperature density ●HE neutrons activate materials around
Li	solid	●Simple moderator ●Low beam energy => 2.5 MeV	●Low melting point 180 ℃ => need fine, absolute , stable temperature control ●Generate radioactive ^{7}Be => 5.2 TB/yr (500hrs operation)=> >20mSv/h in exposure room
	liquid	●Simple moderator ●Low beam energy => 2.5 MeV ●No target damage	●Explosive if mixed with water ●Generate radioactive materials

Figure 4 shows a schematic layout of medical neutron accelerator designed at PMRC [3]. The RFQ and DTL are used as a high power of proton accelerator. A 0.5 mm thick of Be target is selected as a neutron production

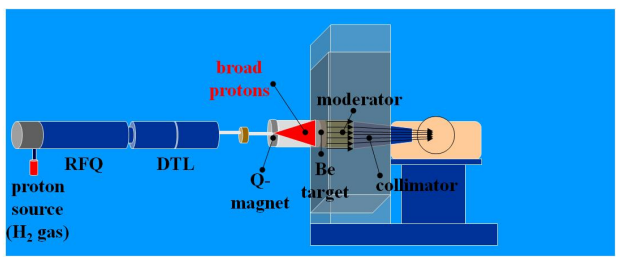

Figure 4: Layout of medical neutron accelerator at PMRC.

target because safety and low radio activity in the treatment room are considered high priority in a hospital. High power injection on the target makes it much high temperature. The Li targets are considered difficult in control of temperature on the target. A pencil beam of protons are once spread out using the Q-magnet before injecting to the Be target to reduce heat density on the target. However, further optimization is still remained to increase neutron intensity for BNCT. The neutrons produced by 8 MeV protons are too fast for BNCT. A moderator is designed to convert the fast neutrons efficiently to epithermal neutrons.

FUTURE PARTICLE THERAPY

In the future, those 3D methods would be expanded into 4D naturally and 5D (4D+biological dimension) eventually. At first, Motion tracking technology would be integrated into the radiation/particle therapy. The current respiration gate system has been used to expose radiation/ particles in only expiration period to prevent dose distribution from getting worse. In this case, beam efficiency during treatment cannot be improved up to 100%. The motion tracking technique would make it possible if a new treatment planning system is developed available for motion using 4D-CT. In addition, size and shape of tumors inside a patient are daily changed. The radiation/particle therapy would evolve adaptive to these changes. Secondary, biological effects in particle therapy have been studied in vitro and in vivo. Relative biological effectiveness (RBE) has been considered in radiation/particle therapy to adjust different effectiveness in treatment for different probe of radiation and particles; x-ray, γ-ray, proton, carbon, neutron, and other lighter ions. The biological effects could be individually different and associated with specific parts of DNA. Eventually the particle therapy would be an individual-order-made (5D) therapy.

FUTURE MEDICAL ACCELERATOR

Advanced accelerator should be developed so as to satisfy those demands mentioned above in the future particle therapy or requests from medical radiation/particle users. Safety, reliability and stability are the most important properties required to the medical accelerators including the beam delivery system, the exposure system, and the peripheral equipments such as electric power system and beam control system. These important properties would be obtained from the integration of many technologies established in various fields and software development making it possible to control whole parts of equipments. Most of the technologies used in the medical equipments should be already known and established before the medical accelerator design. Commercially important thing is to continue R&D for cost down and to achieve compactness and prevalence without new and non-established technologies. The accelerator control must be available and friendly for non-accelerator specialists; medical specialists. One button operation is the best way. One of the possible methods to compact the equipment size and cost is usage of lighter and biologically effective particles.

The state-of-the-art accelerator for BNCT requires high intense source of neutrons. Unfortunately the epithermal neutron intensity is not currently high enough for the

accelerator-based and hospital-based BNCT, which would not be achieved before establishing high intense proton beam, beam delivery method on target, and optimization of target quality; material, dimension, shape, and so forth.

Finally, according to prevalence of the medical accelerator, two types of facilities would be constructed in the future: one using compact single-purpose accelerator in a small space of hospital and the other using integrated multi-purpose accelerators in the already-operating particle therapy facility; for example, integration of proton and neutron therapy using common accelerator.

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