MEDICAL APPLICATIONS OF C-BAND ACCELERATOR TECHNOLOGIES

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Abstract

Electron linacs have been widely used in medical applications. Most of these linacs use S-Band (about 3 GHz) microwave technologies. Recently, however, several new ideas in radiation therapy have been proposed that require new, higher power, higher gradient accelerators. In this paper, we propose the application of C-Band (5 to 7 GHz) technology for radiation therapy. Also, we describe the possible design of a new standing wave accelerator structure and R&D of C-Band technology in KEK.

1 INTRODUCTION

Cancer is the major cause of death in most developed countries, where approximately one in every four persons will develop a cancer at sometime in his or her lifetime. Modern society has recognized the immense value of linear accelerator technology as a powerful tool in medical technology. Today more than 5500 electron linacs are used for medical purposes, mainly for the treatment of cancer, in the world.

2 MEDICAL ACCELERATORS

Linacs play such an important role in radiation therapy because of its treatment efficacy and cost efficiency. One of the difficulties in treating cancer is targeting the treatment at the cancerous cells only, without putting the rest of the body at possible or certain risk, as does often surgery and chemotherapy.

Radiation therapy is a preferable alternative to chemotherapy and surgery, although it is often used in conjunction with both. Nearly half of all cancer patients in developed countries will receive radiation therapy, as definitive therapy, for palliation, or as an adjunct to surgery, and more than 50% will be cured by radiation therapy [1]. Linear accelerators direct the x-ray dosage at the target volume, the cancerous tumor cells, and control their reproduction capabilities. Radiation therapy offers these benefits:

1. It localizes the treatment to the tumor
2. No cuts or abrasions are made on the body
3. The process is moderately tranquil, not traumatic for patients
4. Patients usually do not suffer side effects from radiation therapy
5. Most patients do not need expensive hospital care
6. Smaller medical staff is involved in treatment

However, the x-rays are “equal opportunity destroyers,” killing healthy tissue while traveling to, and through, the target volume. The goal of new radiation therapeutic technology, therefore, is eradication of the tumor with minimal radiation damage to the surrounding healthy tissue while maintaining a high quality of life for the patient.

3 CURRENT RESEARCH IN RADIATION THERAPY

Tomotherapy [2] and stereotactic [3] radiotherapy are new radiation treatments that offer advanced solutions to this enduring problem. Currently, simulator and CT (computer tomography) imaging technology allowing radiation physicians the ability to precisely locate the tumor position before treatment. Modern medical accelerators utilize the most updated computer technology, which has allowed radiation to be delivered to the tumor as a function of time, space and dose rate. The time dependent dose delivery is called "physiological gating," wherein the beam is delivered only over certain time intervals in order to account respiration and heart motion. For space dependence, the multileaf collimator "MLC," which utilized a number of beam absorbing leaves to produce an irregular beam shape in order to "conform" the treatment beam to the prescribed 3-D treatment volume. However, these advanced techniques are still not based on real time tumor monitoring and treatment concurrently. Tomotherapy and stereotactic radiotherapy will allow physicians to locate the tumor position *during* treatment as well, and are able to make modifications to the beam based on real-time analysis, thus making the treatments more proficient and yielding a higher cure rate for its patients. Advances in the ratio of computational power to computer cost are now making this form of therapy economically practical. Between 1970 and 1980, significant advancements in CT and MRI technology made radiation oncology a precise and predictable modality. As a result, the cure rate by radiation therapy has increased dramatically

Figure 1 shows the tomotherapy concept. Tomotherapy combines the precision of a helical CT scan with the potency of dynamic radiation therapy. Using an intensity-modulated fan beam, rotational radiotherapy delivery is achieved by moving multiple collimator vanes in and out of the beam path with speed and precision. By rotating the beam source around the patient, the beam is able to enter the patient from many different angles and to deliver more doses of lesser potency, thereby exposing the healthy tissue to a significantly lower dosage of radiation.

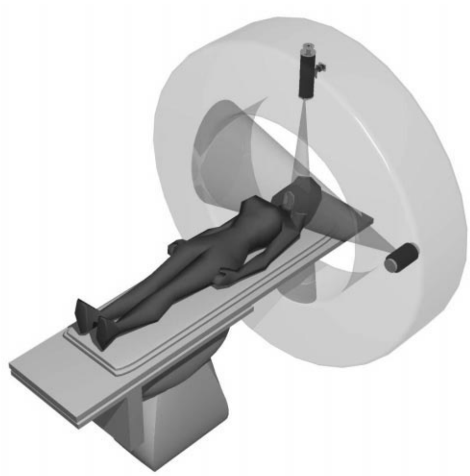

Figure 1: Tomotherapy concept

Thus, tomotherapy accurately controls the location and intensity of the radiation entering the patient with the joint advanced technology of the MLC system and helical CT imaging technology, and delivers highly conformal dose distributions. When using such a capable dynamic modulator, however, one must pay special attention to possible inaccuracies such as leaf transmission, leakage and alignment.

Stereotactic radiotherapy is often prescribed for brain tumors, using extreme precision and a finely focused radiation dosage to the target volume. By directing finely collimated beams of radiation from thousands of angles, the x-rays converge at one small spot, the tumor, while the healthy non-targeted tissue receives very little radiation.

This technique currently requires the use of a head ring, CT scan often in conjunction with magnetic resonance imaging or angiography, and 3-dimensional simulation and computerized dosimetry as well as treatment using a linear accelerator. Figure 2 shows a new concept of stereotactic radiotherapy, which utilizes two rotary joints that are placed on the side of the gantry and the top of ceiling. These provide all the necessary electrical powers and coolings to the accelerator and the X-ray source, which are free to rotate around all angles of the target volume.

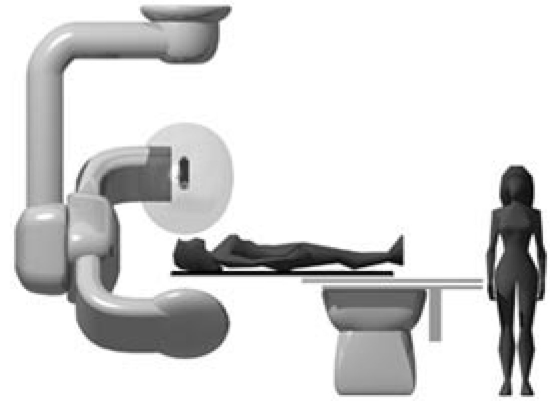

Figure 2: Stereotactic therapy concept

4 MEDICAL ACCELERATORS IN THE FUTURE

Even today's most sophisticated linear accelerator systems for radiation therapy still have many shortcomings. Both tomotherapy and stereotactic treatments require more advanced accelerators that can produce much more x-ray radiation and at a more stable rate, in time and space. They need:

1. A dose rate of 1 Gy/sec or higher
2. X-ray treatment beam position accuracy of 0.1 mm
3. Compact size of the linear accelerator
4. 100% temporal and spatial control of the x-ray beam.

In today's treatment, however, there is not 100% temporal and spatial control; tumor position monitoring is not done in real-time. Simulation is done in another room during the treatment, and what results is bombardment without knowing the exact target. A second issue is the undesirable shift of organs during the radiation treatment, where organs may potentially move 2 cm and thus interfere with the line of radiation.

Advanced equipment such as CT can be used merely for sending and storing information through the network in a sequential manner. What we need is interactive equipment that can produce real time imaging and can feed back immediately (to the degree of a millisecond) to the linear accelerator and deliver the dose at once, thereby eliminating bombardment without knowing the exact target location. This image-directed therapy modifies the radiation source so that the intended target is in the beam line instead of modifying patient position to align with the radiation source. Taking into account natural organ shifts, it is also necessary to deliver the dose in a very short time, requiring a much higher dose rate and a more powerful linear accelerator.

5 C-BAND ACCELERATOR RESEARCH AND DEVELOPMENT

Hence, we propose high-power C-band accelerators to fit the requirements of the accelerators of future radiation therapy. The following summarizes the general description of these C-band accelerators:

1. Compact
2. High gradient
3. High current
4. Stable
5. Mechanically tolerant
6. More efficient

There are many advantages to using higher frequencies for compact accelerators, i.e. higher shunt impedance per unit length, smaller diameter, shorter filling time, and a higher breakdown threshold. Most electrical parameters can be scaled with frequencies but not for mechanical and thermal parameters. As a result, the shunt impedance can not be increased with the rate of $f^{1/2}$ as we wish. The filling time τ will decrease with a frequency of $f^{-3/2}$, which is the advantage for short pulse operation. The voltage breakdown threshold increases roughly by the square root of the frequency [4].

Meanwhile, there are currently several shortcomings in using a much higher frequency, such as a tighter mechanical tolerance, higher power density, and higher power transmission loss. These are true not only for the accelerator itself, but also for RF power sources such as klystrons and magnetrons. Because of tighter tolerance and higher power density, these microwave sources are difficult to make operating reliable at higher peak power.

The High Energy Accelerator Research Organization (KEK) in Japan has developed C-Band components and accelerators that bring solutions to the above-mentioned problems. Among their advanced solutions include:

1. C-Band klystron
2. Pulsed modulator for C-Band klystron
3. C-Band accelerating structure

KEK's C-Band 50MW klystron uses $\pi/2$ mode traveling wave structure in the output circuit in order to enhance the power-conversion efficiency and to reduce the electric field gradient in the output circuit. Operating at about 5700 MHz, the beam voltage reaches about 360 kV. Various tests have demonstrated that the KEK design is powerful and reliable for the multi-cell output structure.

The pulse modulator uses an inverter-type power supply, which eliminated the massive charging-transformer and also the de'Q-ing circuit from the traditional design. KEK's compact modulator design produces test output voltage of 23.4 kV, and a pulse width of 3.9 microseconds. Having followed the concept of the "Smart Modulator," this one tries to satisfy demands that it be reliable, simple, cheap, efficient, and easy to operate.

The C-Band accelerating structure is under development. Table 1 summarizes the design parameters of a proposed compact high power accelerator for medical applications, which utilizes the hybrid standing wave structure (patent pending).

This structure will be able to deliver a much higher dose rate (1Gy/sec) than currently used in the S-band accelerator, provided the successful operation of the new X-ray target concept.

Table 1: Specifications for C-Band accelerating structure

ACCELERATOR LENGTH (cm)	23
STRUCTURE	Hybrid Standing Wave
NUMBER OF ACC. CAVITIES	9
FREQUENCY (MHz)	5712
ENERGY (MeV)	10
BEAM CURRENT (mA)	600
BEAM PULSE WIDTH (μsec)	4
REPITION RATE (PPS)	240
RF PEAK POWER (MW)	11
SHUNT IMPEDANCE (MΩ/m)	140
LOAD LINE (MeV)	15-8 i

6 CONCLUSION

Electron accelerators have been key contributors to the success of radiation therapy. The medical community is always looking for new linac technologies that are more effective and can save more lives. C-Band frequency technology could be the best choice for future applications in radiation therapy.

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