Performance of a Respiration-Gated Beam Control System for Patient Treatment

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Abstract

A beam control system for irradiation treatment gated by respiration of a patient has been developed at HIMAC in order to minimize an unwanted irradiation to normal tissues around tumor. The system employs a position sensitive detector to sense a target movement, an rf-knockout extraction with FM and AM, an optimized operation pattern of HIMAC synchrotron ring, a beam deceleration as a residual beam aborting system, and an interlock system for a safety treatment. The irradiation treatment gated by respiration has begun since June 1996.

1 INTRODUCTION

Clinical study of cancer treatment has been successfully progressing since June 1994 by using carbon beams from a heavy ion medical accelerator HIMAC[1]. Heavy ion beams are very suitable for cancer treatment because of the high dose localization and the high LET characteristic. A high irradiation accuracy is required in the treatment, however, because of its characteristics. In particular, damage to normal tissues around tumor is inevitable in treatment of a tumor moving along with respiration of a patient. A respiration-gated beam control system, which can respond quickly to irregular respiration, therefore, has been developed at HIMAC[2].

The design considerations and the performance of the system are reported in this paper.

2 DESIGN CONSIDERATIONS OF BEAM CONTROL SYSTEM

The system for the irradiation gated by respiration requires essential design considerations as follows; 1) a permitting-irradiation signal should be accurately generated to permit irradiation only when target is at the designed position. 2) a start and stop of beam extraction should respond quickly to a trigger signal. 3) an operation pattern of the ring should be optimized to give maximum effective irradiation dose-rate. 4) an aborting system of residual beam should be provided to avoid undesired activation. 5) an interlock system for a safety treatment should be applied.

An operation pattern of the system for the irradiation gated by respiration is schematically shown in fig. 1.

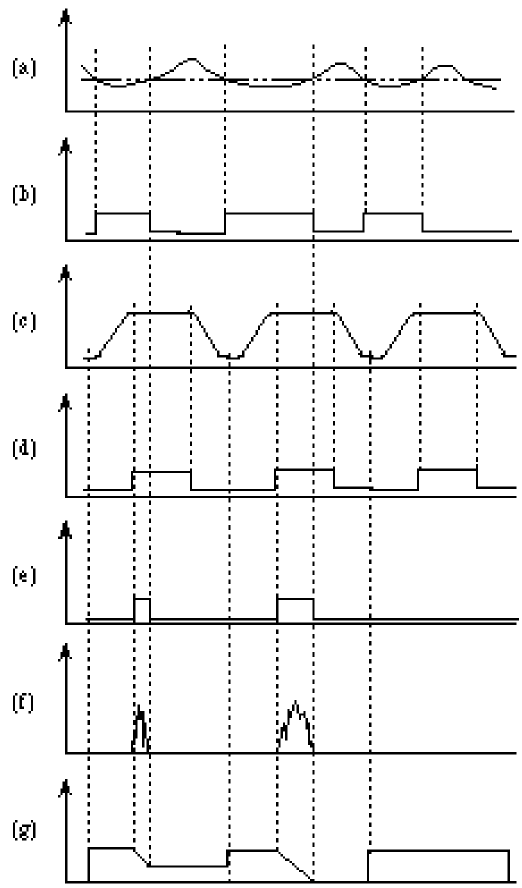

Figure 1: Schematic operation pattern of the system for irradiation gated by respiration. (a) Respiration signal, (b) Permitting-irradiation signal,(c) Operation pattern of ring, (d) Flat-top signal, (e) Beam on/off signal, (f) Beam spill, (g) Circulating beam intensity.

2.1 Permitting-irradiation signal

It is very important to detect accurately a target movement for the irradiation gated by respiration. A position sensitive detector (PSD) with an infrared light source is chosen in order to generate the respiration signal because of its reliability, stability, and easy setting.

The permitting-irradiation signal should correspond to an expiratory phase, further, because a target movement is usually small during this phase and the position is more stable against the fluctuation of inspiration. The permitting signal is generated by using the respiration signal and a threshold level, only when the respiration is in the expiratory phase.

2.2 Extraction method

Concerning the irradiation gated by respiration, it is essential to start and stop beam extraction promptly according to the beam ”on/off” signal generated by using the permitting-irradiation signal and the flat-top one. The system employs the rf-knockout extraction method with amplitude and frequency modulation[3]. The rf-knockout extraction utilizes a horizontal emittance growth by applying a transverse rf field resonated with a horizontal betatron tune, while a separatrix is kept constant. The transverse rf electric field is applied with frequency and amplitude modulation. The frequency modulation increases an extraction efficiency because it broadens a frequency band-width corresponding to a horizontal tune spread at a resonant extraction. The amplitude modulation can control a spill envelope of an extracted beam. Advantages in the present method are 1) prompt response to start and stop of the beam extraction by turning the transverse rf filed on and off, 2) flexibility of a start/stop timing of an extraction at the flat-top because the fields of all extraction elements are kept constant during the flat-top, and 3) a small emittance in the horizontal plane due to a constant separatrix. The results from experiments showed that the response was within 1ms and the horizontal emittance was reduced by about 70% compared with that by the ordinary resonant extraction without the deterioration of the extraction efficiency.

2.3 Operation pattern of the ring

To optimize an operation pattern of the ring, it is assumed that a respiration pattern is independent of the operation one, an irradiation is continued infinitely, and an extracted beam intensity per one cycle is kept constant. Under the condition, effective irradiation dose-rate is maximized at an extraction duty factor of 50%, because a beam can be extracted as long as the flat-top signal is coincident with the permitting irradiation one. If the beam intensity per one cycle can be infinitely increased, on the other hand, the effective dose-rate is increased as increasing the duty factor. At HIMAC, the effective dose-rate is maximized at the duty factor of 50% in the 0.3Hz operation pattern. The effective dose-rate in this operation can be kept at the operational value if the beam intensity is increased by 70%, which can be easily realized.

In order to reduce effective irradiation period for treatment, all of the accelerated beam should be extracted as soon as the ”beam on” signal is generated. An irradiation period more than 10 times longer than that of wobbling magnets is required, on the other hand, in order to obtain a uniform dose in the lateral distribution. The amplitude of a transverse rf field for rf-knockout extraction is determined so that all of the beam is extracted during about 400ms, therefore, while the flat-top period is about 1500ms in the 0.3Hz operation pattern.

2.4 Residual beam aborting system

The residual beam is to be aborted around the ring, because the accelerated beam should not be extracted from the ring unless a ”beam on” signal is generated. As a beam aborting system, thus, deceleration of the residual beam from a top energy to an injection one was proposed in order to avoid unwanted activation around the ring. The deceleration efficiency from the top energy of 400MeV/n to the injection one of 6MeV/n was 71% as a result of the test[4].

2.5 Interlock system

An interlock system for radiation safety has been also used in dose control of treatments at HIMAC. One of the most important functions of the interlock system is to protect against unauthorized irradiation in the treatment. It must be avoided for beams to be extracted during the ”beam off” period in the irradiation gated by respiration. Such an extraction may be occurred by a current ringing of the main power supply of the ring, for example. To assure quality of the irradiation gated by respiration, therefore, protection of such the irradiation is added to the interlock system. The interlock works immediately when irradiated dose in the period of not permitting-irradiation exceeds a threshold level, and beam extraction is stopped within 10ms by increasing the horizontal tune from the resonant one of 11/3. At same time, a fast beam shutter is closed within 300ms.

3 PERFORMANCE

3.1 Penumbra size

An irradiation gated by respiration was experimented by using a phantom moving along with a simulating signal of respiration[2]. In the experiment, the ring is operated by a cycle of 0.3Hz with a duty factor of 45%, and carbon beams with the energy of 290 and 400MeV/n are extracted. Further, a phantom placed at the isocenter is moved with a stroke of 22mm and, is driven by a 0.25Hz sinusoidal signal that prevents respiration. A collimator with an aperture of 40mm square is placed in front of the phantom to define an irradiation field, and is 450mm distant from the phantom. A penumbra size in three cases, i.e, a fixed phantom, a gated irradiation to moving phantom, and an ungated irradiation to moving phantom were investigated by measuring a density of an exposed X-ray film attached with phantom. The penumbra size of 2.5mm in the fixed phantom is naturally less than those in other cases. However, the penumbra size in the gated irradiation is considerably reduced to 5.5mm from 15mm in the ungated one.

3.2 Irradiation gated by respiration

The system for irradiation gated by respiration was tested, after checking the generation of each gate signal and tuning the rf-knockout extraction and the beam deceleration in the optimized operation pattern of the ring. In the test, the irradiation condition was set through the beam delivery control system, and the respiration signal was generated by the PSD with the infrared light source set on a human body in order to simulate the treatment gated by respiration. In addition, parameters of the transverse rf field and the timing of the flat-top signal were set through the synchrotron control system as well as the operation parameters of the ring. The typical result is shown in fig. 2. As can be seen in the figure, the beam extraction is stopped within 1ms immediately when the "beam off" signal is generated, and the residual beam is decelerated to the injection energy with its efficiency of 70%. The irradiation time for obtaining a planned dose was increased by about 30% compared with that in treatment of without gating. However, the irradiation time can be easily reduced to that in treatment of a fixed target by increasing the beam intensity. Concerning the test of the interlock system, the interlock system was verified by using the delayed "beam on/off" signal by about 200ms, because the beam can be extracted by the delayed "beam on/off" signal even if the permitting-irradiation signal is not generated. The irradiation gated by respiration has been carried out since June 1996, after the test of the system and an instruction to operators.

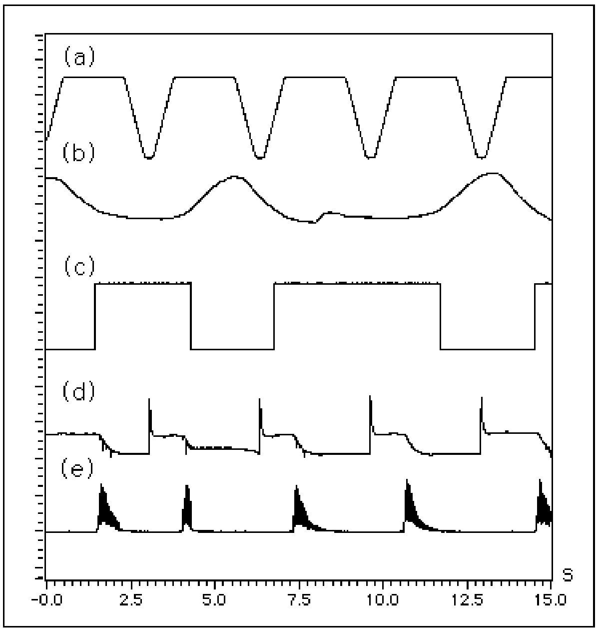

Figure 2: A test for respiration-gated beam control system. (a)Current pattern of the main magnet of the ring, (b)Respiration pattern, (c)Permitting irradiation signal, (d)Circulating beam intensity by an electrostatic position monitor, (e)Spill of extracted beam.

4 CONCLUSION

The beam control system for irradiation treatment gated by respiration has been developed at HIMAC. The penumbra size was measured by using a phantom moved along with the simulating signal, and was considerably reduced to 5.5mm to 15mm in the ungated irradiation. As results of the test of the system, further, the irradiation gated by respiration was successfully achieved, and the interlock system worked also very well.

The system will play an important role in clinical study such as treatment for a lung or liver cancer moved along with respiration of a patient.

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