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Original Article

Latency Characterization of Gated Radiotherapy Treatment Beams Using a PIN Diode Circuit

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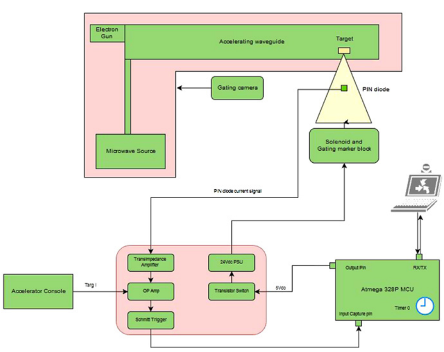
Graphical abstract



Abstract

Background: Radiotherapy is based on the premise of accurate dose delivery to target volumes within a patient, while minimizing dose to surrounding tissues. Recent developments in the treatment of breast cancer have focused on "gating" the delivery of the treatment beams to minimize the effect of patient motion during treatment, and increasing separation between the target volume and organs at risk (OAR), such as lung, heart and left anterior descending coronary artery. The basic principle involves rapidly switching the treatment beam on or off depending on the patient breathing cycle. It is therefore important to know the characteristics of gated treatments such as latency.

Methods: In this work an electrical PIN diode circuit (EPDC) was designed for quality assurance (QA) purposes to examine beam latency timing properties. Evaluation of the EPDC was performed on a TrueBeam™ (Varian, Palo Alto) linear accelerator and its internal gating system. The EPDC was coupled to a moving stage to simulate a binary pattern with fast beam triggering within predefined limits, the so called "gating window". Pulses of radiation were measured with the PIN diode and the results were compared to measurements of current produced across the linac target. Processing of the beam pulses and calculation of the latency timings was performed by an Atmega328P microcontroller.

Results: For beam-on latencies, 2.11 ms (6 MV) and 2.12 ms (10 MV) were measured using the PIN diode, compared to 2.13 ms (6 MV) and 2.15 ms (10 MV) using the target current signal. For beam-off latencies, 57.69 ms (6 MV) and 57.73 ms (10 MV) were measured using the PIN diode, compared to 57.33 ms (6 MV) and 56.01 ms (10 MV) using the target current.

Conclusions: PIN diodes can be used for accurate determination of the beam-on and beam-off latency characteristics, which could potentially lead to improvements in gated radiotherapy treatments, for example optimizing the gating windows and in estimating dosimetric errors associated with treatment beam latencies.

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1. Introduction

The main premise of radiation therapy is to maximize the dose delivered to the target volume while minimizing the dose given to the surrounding healthy tissue. Developments of new treatment techniques in conjunction with advances in equipment technology seek to improve this ratio even further. Respiratory motion represents one of the major challenges in radiation therapy, especially in abdominal or lung treatments [1]. Additionally, separation between target volume and OAR can be strongly affected by breathing motion.

Optical systems for monitoring respiratory motion and controlling beam-on and beam-off are common and are based on either tracking markers attached to the patient, or scanning the patient surface directly in order to compensate for respiratory motion and organ shifting by interrupting the treatment beam when the patient surface (and by extension, the target volume) is outside predefined limits. Some gating devices, like the Real-time Position Management^{TM} (RPM^{TM}) system (Varian, Palo Alto), are already integrated into the linear accelerator, while others are external. External devices like the Sentinel^{TM} (C-Rad, Sweden) and Catalyst^{TM} (C-Rad, Sweden) systems require an interface to connect to the Linac. Quality control (QC) methods like measurement of beam energy, output and geometry is needed to ensure optimal functionality of the accelerator. In addition to this, gating functionality requires monitoring of other factors relating to temporal accuracy of phase/amplitude, gating windows used, calibration of the phantom used for respiratory phase/amplitude and also tests of the interlock system [2]. Of particular importance regarding gated treatments is the beam-on and beam-off latency characteristic of the radiation beam. Beam-off latency is the most critical of these parameters to ensure that dose is not delivered when the target volume is assumed to be outside of the planned treatment position. The latency depends on the type of linear accelerator and the type of gating system used. Any delays can have undesired effects on the planned dose distribution of the treatment. Latency is also an important factor to consider in 'tracking' treatment modes e.g. Cyberknife^{TM} (Accuray, Madison) [3].

Radiation produced by the linear accelerator consists of beam pulses, generated in the beam-on state. To produce radiation, electrons have to be accelerated inside the linacs waveguide. The so called electron gun serves as an electron source and consists of a filament, a cathode and a grid. By applying a voltage to the filament, the cathode is indirectly heated, resulting in thermionic emission of electrons. Electrons are boiled off the cathode into the space charge region, located between the cathode and the grid. Electrons remain in the space charge region as long as the grid bias voltage is more negative than the cathode. A positive voltage pulse with a width of about 4–5 µs applied to the grid, makes it more positive with respect to the cathode and electrons pass into the accelerating waveguide, which is filled with radiofrequency (RF) produced by the klystron. The electrons are accelerated close to the speed of light (0.99c) while propagating through the waveguide. At the end of the waveguide their path is changed with the help of a bending magnet and the electrons hit a target disk of high density, high Z material (typically tungsten). When electrons hit this target, high-energy Bremsstrahlung photons are produced. Without a high-voltage pulse applied to the grid, no electrons are injected into the accelerating waveguide and therefore no radiation is produced. For gated treatment beams, radiation should only be produced within certain predefined limits, also known as the "gating window" which is specific to each patient. In most of the common gating techniques like amplitude gating, phase gating or breath-hold gating, radiation is produced when the patients breathing pattern passes the lower limit of this gating window during inhalation, and should interrupt when the breathing pattern falls below the lower limit of the gating window during exhalation. In the beam hold state of the accelerator, the gun pulses are offset relative to the RF power pulse from the radiofrequency source of the linac so that no radiation is produced. In this way the linac remains in a stable state whereby the beam can be quickly switched back on.

Different approaches to measure the beam-on and beam-off latencies have been made.

Freislederer et al. used radiographic film and a moving phantom to simulate a patient's breathing pattern and measure the associated dose distribution [1]. The same method was used in the approach of Smith and Becker [4]. Chugh et al. also used a film based method and compared different gating techniques and motion shapes [5].

According to the American Association of Physicists in Medicine (AAPM) task groups 142 report, beam latencies should be within a recommended tolerance of 100 ms (corresponding to an error of ∼1 dose monitor unit (MU) for typical clinical linacs operating at standard dose rates). To our knowledge, no commercial tools are available at this time to measure the beam latency characteristics of medical linear accelerators with high accuracy [2,4,6].

The aim of this work was to design an electrical PIN diode circuit (EPDC) which is able to measure beam-on and beam-off latencies of gated radiation beams and which can be used with different combinations of accelerators and gating systems. This would provide a usable QA tool for radiotherapy clinics that want to examine latencies with a direct measurement method. To verify the functionality of the circuit, beam-on and beam-off timings were calculated by using two independent signals for comparison purposes.

2. Material and methods

In this work, the linacs internal gating system consisting of a gating marker block (Varian, Paolo Alto) and an infrared Polaris