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TECHNICAL PAPER

An affordable custom phantom for measurement of linac time delay in gated treatments with irregular breathing

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Abstract

Respiratory gated treatments are now common in order to reduce tumour motion uncertainties due to breathing. One issue associated with gated treatments is the time delay between the gating system and the linear accelerator. In this study we develop and characterise an affordable phantom to be used in routine and patient specific quality assurance (QA) of the Varian Real-Time Position Management™ (RPM) system. A photodiode has been incorporated into the phantom in order to estimate the time delay. A commercial Quasar phantom was customised to incorporate two stepper motors which independently control an anterior–posterior abdomen/thorax moving plate, and an inferior-superior moving lung insert. A photodiode placed in the path of the radiation is used to measure when beam on/off occurs. Two Arduino microcontroller boards have been utilised to control the motors, read the photodiode and write to an SD card. The measured beam on/off, correlated to the known positions of the phantom is compared to the gate window for RPM. The time delay was measured for sinusoidal movements with a period of 7.50 s and 3.75 s, and for three patient breathing traces. For the sinusoidal movements, time delays of 150 ± 34 ms and 39 ± 34 ms were measured, for 7.50 s and 3.75 s periods, respectively. In the case of the patients' breathing traces time delays of 135 ± 26 ms, 137 ± 34 ms and 129 ± 28 ms were measured. An affordable motion phantom has been developed for routine and patient specific QA of respiratory gating systems. It is capable of reproducing a patient's breathing waveform and performing time delay measurements with a photodiode. Results indicate a time delay of the order of 0.1–0.2 s for the RPM system.

Keywords Respiratory gating · Motion phantom · Time delay

Introduction

Respiratory motion is an issue in radiotherapy because it results in tumour and organ at risk displacement, which may be different between planning and treatment. One method to reduce the impact of tumour motion is respiratory gating. Respiratory gating is typically performed using an external marker which is placed on the patient's thorax or abdomen as a surrogate for tumour motion. One commonly used device is the Real-Time Position Management™ (RPM) system (Varian Medical System, Palo Alto, USA). This system uses an infrared camera to track the movements of a reflective marker. During respiratory gating, the radiation beam is activated when the patient's breathing trace is within a pre-set gated window. The gated window is chosen at a point when the tumour motion is estimated to be low, this is generally the exhale phase where the breathing movement is reproducible, tumour motion is low, and duty cycle longer [1]. In this approach it has been shown that the planning target volume can be reduced by 50% for 15% of patients [2]. A disadvantage of respiratory gating is that it relies on a consistent time correlation between the external marker and internal anatomy [3]. Any phase shift between the two from the time of CT to treatment can cause geometric misses [4, 5].

AAPM TG-142 suggests the importance of measuring the temporal accuracy for gate-on time delay for respiratory gating and recommends this to be measured annually with a tolerance of 100 ms for speeds no greater than 20 mm/s, corresponding to a positional uncertainty of 2 mm [6]. Time delay is the delay for the linac to beam-on

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once the breathing trace is within the gating margin. Various methods have been reported to measure the time delay including the use of the MV and KV imaging systems [7, 8] or by using radiographic or radiochromic film and measuring the amount of blurring [9]. While these approaches for measuring the time delay are powerful commissioning tools, they can be quite time consuming for routine use and generally require constant speed movements in order to determine the time delay accurately.

Recently, Wiersma et al. reported on the use of a photon diode placed at the linear accelerator isocentre to record the beam on/off, during gating on a oscillating platform [10]. Both the potentiometer from the oscillating platform and the photon diode were recorded using an oscilloscope. A high temporal resolution on the time delay in beam on/off during gating could now be performed [10].

The purpose of this project was to develop a motorised phantom with interface software allowing programmable motion for routine QA of the RPM system. The requirements of the system were:

- low cost,
- customisable,
- easy to use,
- preparation and analysis needed to be as automated as possible,
- produce accurate and reproducible movements,
- reproduce a patient's irregular breathing trace,
- capable of measuring the time delay.

In order to measure the time delay of the RPM system not only for constant speed motion but also for patient specific breathing traces, a photodiode was incorporated into the phantom. This way the photodiode could measure the beam on/off times during phantom movement.

Materials and methods

Phantom design

Figure 1 shows an image of the phantom. It consists of a Quasar body phantom (Modus, Canada) with two stepper motors (FL57STH51-2804A, Ocean Controls, Seaford, and Vic, Australia), and two stepper motor drivers (DM442, Ocean Controls, Seaford, and Vic, Australia) to move an anterior/posterior plate and a superior/inferior cylinder. A blackened photodiode (BPW34, Element14, Australia), with a reverse bias, is placed in the beam to measure the beam on and beam off times. Two Arduino boards are used to control the phantom, these are inexpensive, open source prototyping platforms which have a number of analogue and digital inputs and outputs. The two boards are named motor control and detector readout for the following sections.

Three superior/inferior cylinders have been constructed for various uses of the phantom, shown in Fig. 2. These consist of a film insert, an ion chamber insert and an insert incorporating a higher density object (i.e. tumour).

Process

The process by which the phantom operates is that either a sinusoidal or RPM-measured patient breathing waveform (*.vxp file) is binned into 100 ms samples, as shown in Fig. 3. A file with the required distances to travel every 100 ms is then exported to the motor control board.

The motor control board then reads the distance file through an SD card, and computes the required pulses, N_{pulses}, to send to the stepper motors to produce that distance, D, every 100 ms using Eq. (1):

$$N_{pulses} = \frac{D \times S}{P} \tag{1}$$

where P is the pitch of the stepper motor thread and S is the number of steps the motor turns for one revolution.

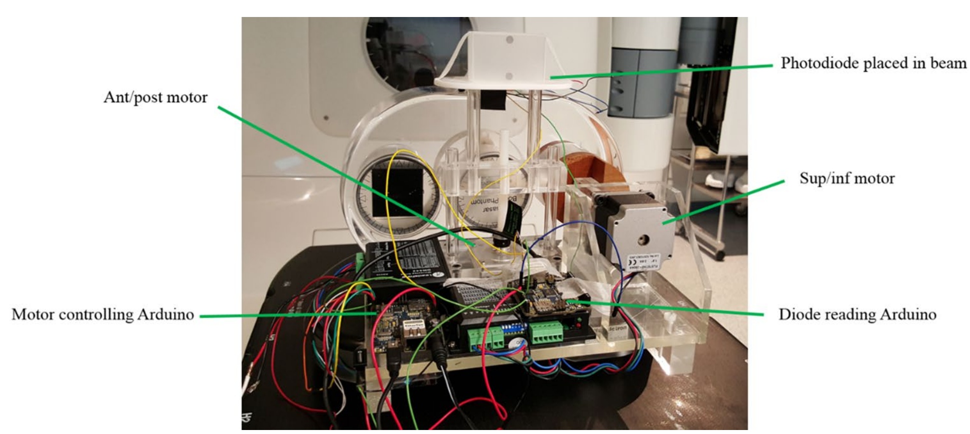

Fig. 1 The motion phantom including two stepper motors controlled by two Arduino boards, and a photodiode placed in the beam's path

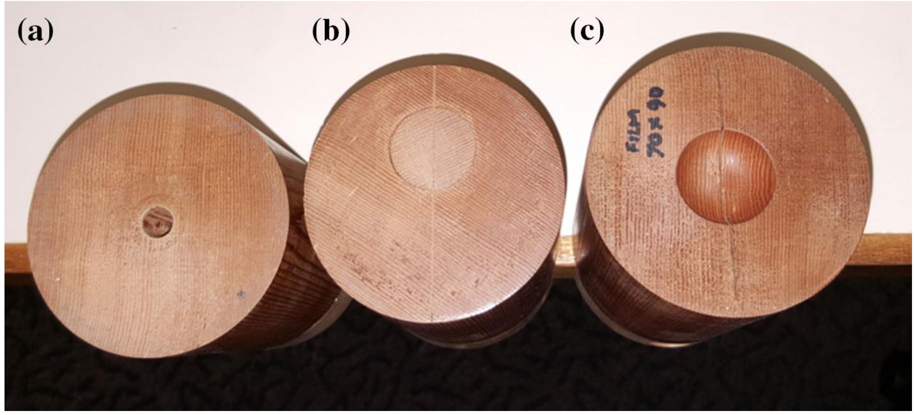

Fig. 2 The three cylinders developed for: **a** an ionisation chamber insert, **b** a variable density object insert and **c** a film insert

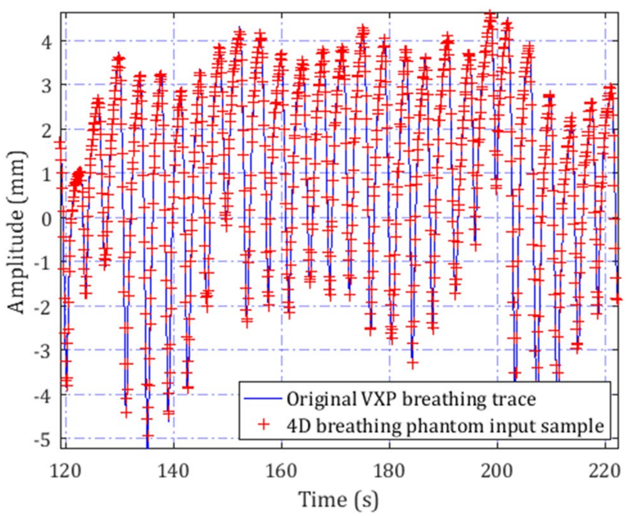

Fig. 3 A patient's irregular breathing trace, binned into 100 ms samples shown in red crosses

For the current design P = 1/6.7 cm and S = 400 pulses/rev. The motor control board then outputs the number of pulses required within the 100 ms to the stepper motor driver, which in turn controls the stepper motor to produce the required turns, shown in Fig. 4a. After every pulse sequence the motor control board outputs to a file the time and the distance travelled. The motor control board also synchronises the time zero with the detector readout board, shown in Fig. 4b, which is continuously reading the photodiode, and outputting to a file the time and photodiode signal. The photodiode is placed within the radiation field in order to record when radiation is being emitted, shown in Fig. 4c.

Automated software

In order to automate this process for ease of use in routine QA of the RPM system, a standalone application was developed in MATLAB (MathWorks, Natick, USA). This program can produce a sinusoidal movement, reproduce a patient's breathing trace and analyse the movement, RPM and photodiode results. By importing the *.vxp file from RPM on the linac, the gate window can directly be compared to the diode measurements and the time delay computed. An example of the program is shown in Fig. 5.

Maximum speed spreading

It was observed that the current design has a maximum speed of 8 mm/s which is due to the limit of the motor speed and also the pitch of the thread. Figure 6 depicts the significant effect which this maximum speed has: the phantom is unable to reproduce the sharper breathing movements. This results in the phantom's movements trending to one direction which would inevitably damage the phantom. Obviously, this does not mimic the patient's breathing trace.

To compare with other phantoms, Dunn et al. developed a similar phantom and reported a maximum speed of 16 mm/s, the difference is that our design has a thread with twice the pitch [11]. To deal with this limitation in the current design, a "maximum speed spreading" approach is incorporated in the preparation software. This approach searches through the input file for the motor control board and if a required displacement is greater than that achievable at the maximum speed, then the phantom will move at the maximum speed and make up the missing displacement in the following temporal bins to compensate. Figure 7a shows the phantom movement using the "maximum speed spreading" and Fig. 7b shows the phantom movements with a maximum speed of 16 mm/s. While the limited maximum speed may be an issue for some irregular breathing, the "maximum speed spreading" approach allows the phantom to mimic the irregular trace.

Time delay measurement

The time delay for a Varian Trilogy linac (Varian Medical System, Palo Alto, USA) using the RPM system was measured using the phantom discussed. The time delay was

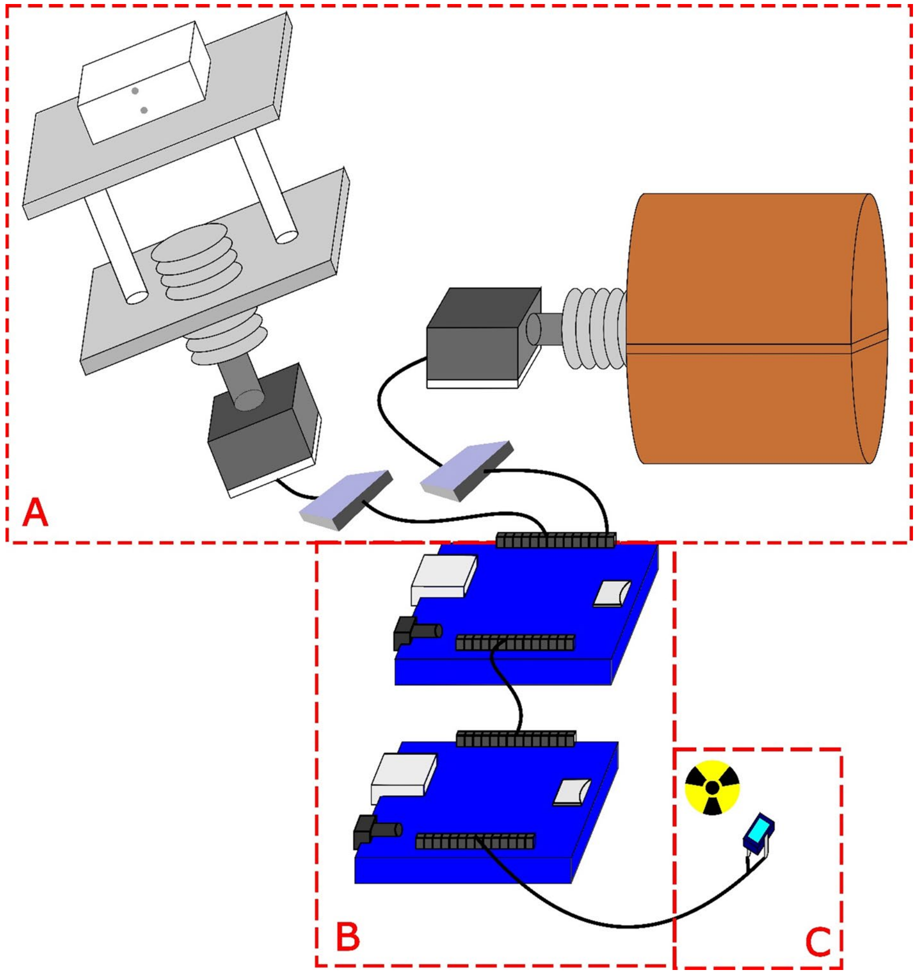

Fig. 4 Respiratory phantom control schematic, **a** shows the anterior/posterior and superior/inferior motions components, **b** the two Arduino boards which control the motors and read the photodiode and **c** the photodiode placed in the radiation beam to record the beam on/off times

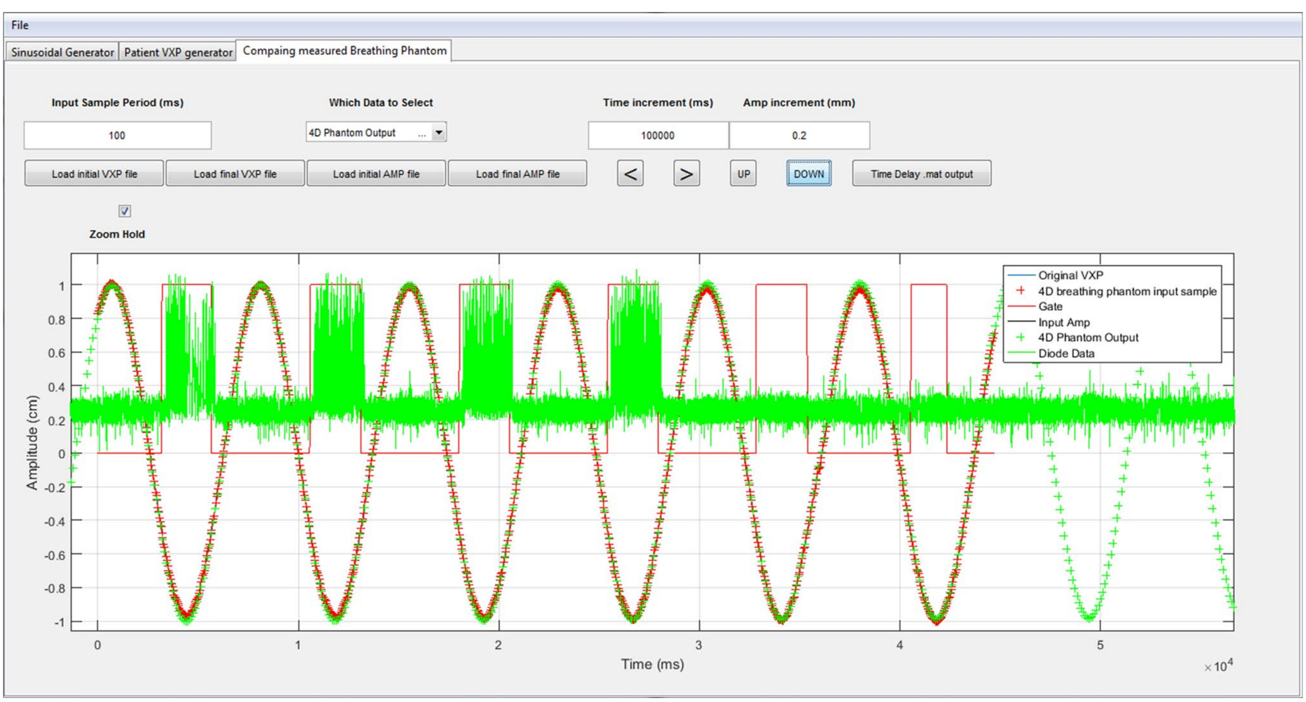

Fig. 5 The standalone preparation and analysis software showing the analysis of the movement, RPM and photodiode results

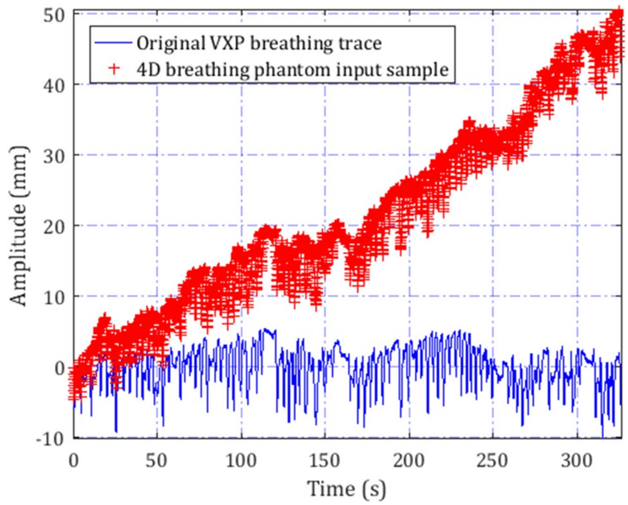

Fig. 6 An irregular patient's breathing trace and the phantom's movements when a maximum speed of 8 mm/s is introduced

measured with the phantom performing sinusoidal movements with a period of 7.50 s and 3.75 s. Measurements were also performed for phantom movements from three patient breathing traces.

Results

Movement accuracy

The movement accuracy of the phantom was affected by optimisation of the Arduino script to control the motor control board, especially for the writing to file operation. Figure 8 shows the effect that different data output approaches have on the movement accuracy when the phantom is attempting to produce a 7.5 s period sinusoidal movement. At first, after each pulse sequence the motor control board was opening the SD card, writing the time and position to file and closing the SD card. As expected this is a slow process as shown in Fig. 8, where the phantom was taking too long to produce the movements. A switch was then introduced into the phantom to tell the phantom when to open and close the SD card, which meant that after each pulse sequence it was only required to write time and position. This approach resulted in a significant improvement but still unable to accurately produce the movements. Even when not writing to file at all, the phantom was still not accurate. Finally, a systematic delay of 17 ms was introduced to account for the time that the motor control board takes to compute and write to file, which closely matches the objective.

Arduino board synchronisation

Synchronisation between the motor control board and the detector readout board is crucial for accurate time delay measurements. This is to ensure that any delay measured in the gating system is not due to a delay between the two Arduino boards. In order to characterise the time zero synchronisation both boards were setup to read the same photodiode and compare the initial irradiation time. Figure 9 shows the signal measured by both the motor control and detector readout boards when the same photodiode is exposed to ionising radiation. A small time delay is observed between the two boards of 47 ± 5 ms. This delay was accounted for in the subsequent time delay measurements.

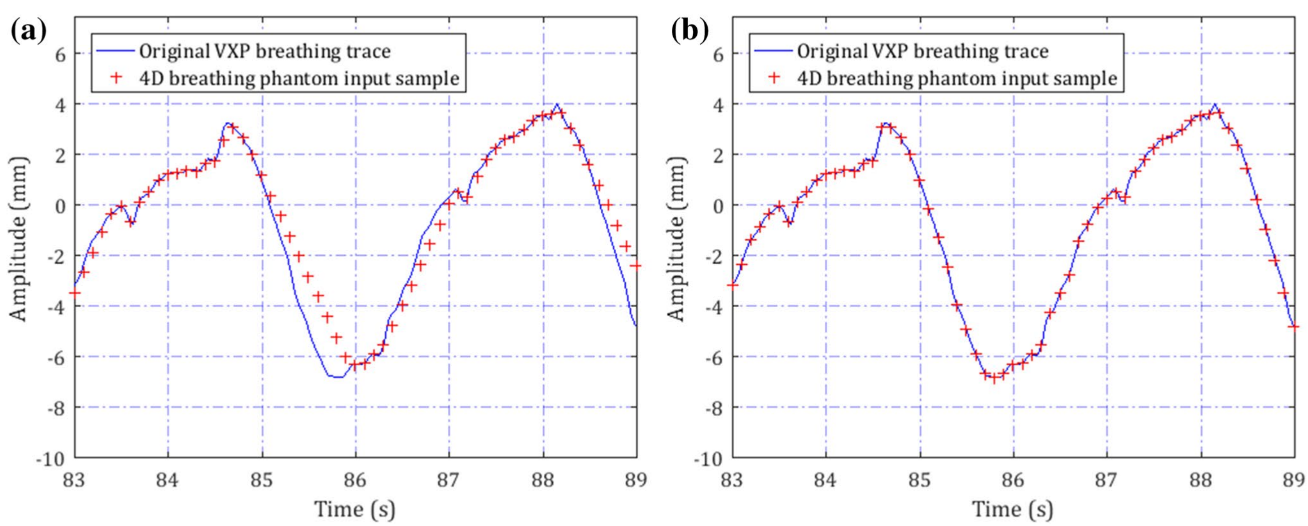

Fig. 7 An irregular patient's breathing trace with **a** the phantom with a maximum speed of 8 mm/s and using the "maximum speed spreading" approach, and **b** the phantom with a maximum speed of 16 mm/s

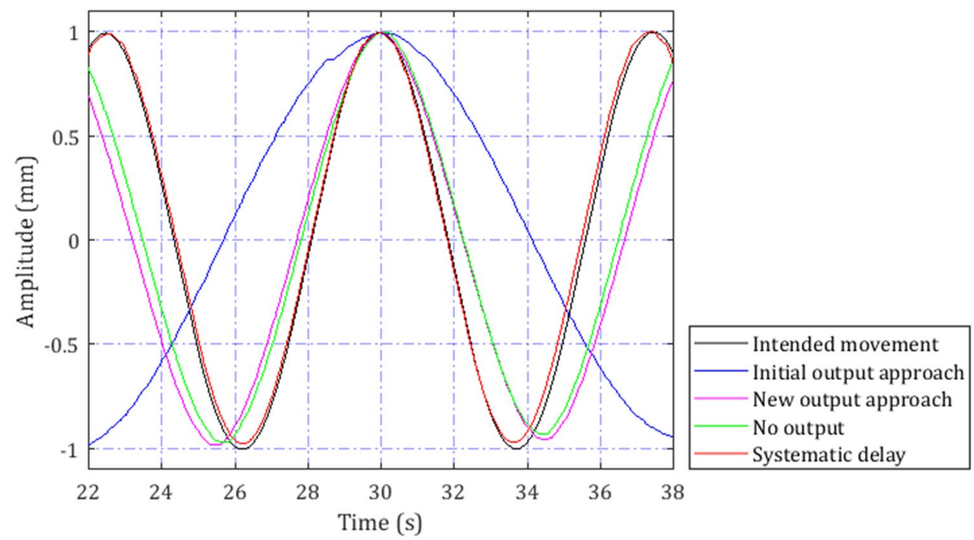

Fig. 8 The effect of the Arduino script on the movement accuracy for a 7.5 s period sinusoidal movement, showing the intended movement, the initial output approach, the new output approach, no output and the use of a systematic delay in pulse calculations

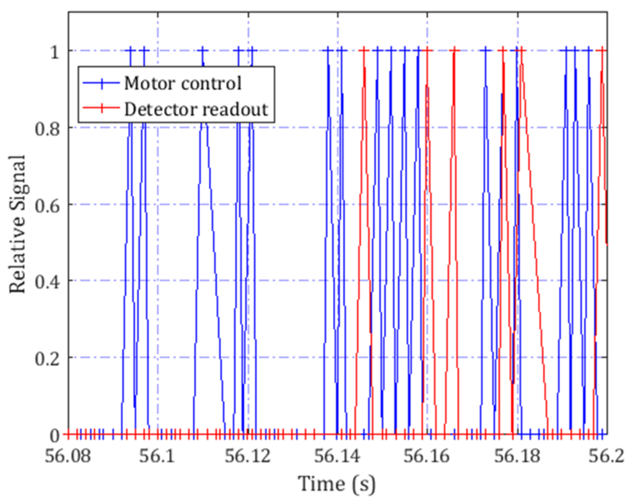

Fig. 9 The motor control board and detector readout board recording the signal for the same photodiode when exposed to ionising radiation

Time delay measurements of the linac RPM system

Time delay measurements were performed for a sinusoidal movement of 7.50 s period, a faster movement of 3.75 s period and for three different patients' breathing traces. The time delay in the gated beam on was measured by comparing the RPM gate signal and the photodiode measured signal of the x-ray radiation, and subtracting the delay measured between the two Arduino boards. For the sinusoidal movements a time delay of 150 ± 34 ms and 39 ± 34 ms was measured, for the 7.50 s and 3.75 s periods, respectively. In the case of the patients' breathing traces a time delay of 135 ± 26 ms, 137 ± 34 ms and 129 ± 28 ms were measured for each of the three patients' breathing traces. The uncertainties given are a standard deviation of the measured time delay. These values are in agreement with that reported by different approaches [8].

Conclusion and future work

A phantom capable of reproducing patients' breathing traces has been developed for routine quality assurance of the Varian RPM system. The phantom incorporates a photodiode for measurement of the beam on/off time in order to easily and routinely measure the time delay in the gating system. A standalone program was developed to automate and simplify the use of the phantom. For interested readers, we are happy to provide the Arduino codes and analysis software.

For our RPM system a time delay of 39–150 ms has been measured for sinusoidal and patient breathing traces. One major advantage of the photodiode system is that the time delay can be measured for varying speeds and irregular breathing patterns, such as a patient's breathing trace. Other approaches require constant speed movements in order to determine the time delay [7].

The current design of the phantom has a limiting maximum speed of 8 mm/s, to overcome this a "maximum speed spreading" approach has been developed. A future modification of the phantom will be to install a thread with a coarser pitch to increase the maximum speed. Further work will include investigation of backlash mitigation to improve positioning accuracy, and to perform radiochromic film measurements in the superior/inferior cylinder with comparison to photodiode measurements. In this way we can compare the amount of dose blurring observed in the film with the time delay measured by the photodiode.

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Compliance with ethical standards

Conflict of interest All authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

References

1. Giraud P, Houle A (2013) Respiratory gating for radiotherapy: main technical aspects and clinical benefits. ISRN Pulmonol 2013:13
2. Underberg RWM et al (2005) Benefit of respiration-gated stereotactic radiotherapy for stage I lung cancer: an analysis of 4DCT datasets. Int J Rad Oncol Biol Phys 62(2):554–560
3. Ge J et al (2013) Accuracy and consistency of respiratory gating in abdominal cancer patients. Int J Rad Oncol Biol Phys 85(3):854–861
4. Vedam SS et al (2001) Determining parameters for respiration-gated radiotherapy. Med Phys 28(10):2139–2146
5. Li R et al (2012) Evaluation of the geometric accuracy of surrogate-based gated VMAT using intrafraction kilovoltage x-ray images. Med Phys 39(5):2686–2693
6. Klein EE et al (2009) Task Group 142 report: quality assurance of medical acceleratorsa). Med Phys 36(9):4197–4212
7. Woods K, Rong Y (2015) Technical Report: TG-142 compliant and comprehensive quality assurance tests for respiratory gating. Med Phys 42(11):6488–6497
8. Jin J-Y, Yin F-F (2005) Time delay measurement for linac based treatment delivery in synchronized respiratory gating radiotherapy. Med Phys 32(5):1293–1296
9. Smith WL, Becker N (2009) Time delays in gated radiotherapy. J Appl Clin Med Phys 10:140–154
10. Wiersma RD et al (2016) Technical note: high temporal resolution characterization of gating response time. Med Phys 43(6Part1):2802–2806
11. Dunn L et al (2012) A programmable motion phantom for quality assurance of motion management in radiotherapy. Australas Phys Eng Sci Med 35(1):93–100