Development of a Cardiac and Respiratory Phantom (CARP) for use in Radiosurgery Dosimetry

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Abstract—**Cardiac Radiosurgery is one of the newest modalities for management of ventricular tachyarrhythmia (VT). It precisely targets radiation to the heart using a high-dose single fraction treatment to scar or destroy cardiac tissue that is allowing irregular electrical signals. Patients often have ICDs with leads that have metal components close to the targets for treatment within the heart. These ICD leads are easily distinguished in kilovolt imaging avoiding any need for additional invasive surgery to implant fiducial markers within the patient. Although respiratory motion management techniques are well established in the radiotherapy setting, there are currently no commercially available systems that evaluate the effects of cardiac motion on respiratory tracking. The cardiac and respiratory phantom (CARP) is designed to mimic cardiac-coupled respiratory motion for use in determining the ability of a medical linear accelerator to track an ICD lead as a motion surrogate. The phantom displaces a platform, which can house ICD leads and dosimeters, in the cranio-caudal and medial-lateral directions. The cardiac and respiratory rates and displacements are user controlled through a computer which is coupled to the phantom by an Arduino. The CARP can achieve up to 150 breaths and 250 cardiac beats per minute to within a 1% error, for standard displacements. The total cardiac and respiratory travel ranges achieved are 3.5 and 4cm, respectively. The CARP can successfully be used as a quality assurance tool in the setting of tracked radiosurgery for cardiac targets.**

Keywords— **Cardiac, defibrillators, radiosurgery, dosimetry**

I. INTRODUCTION

Cardiovascular disease is the number one cause of death worldwide and 80% of cases are caused by ventricular tachyarrhythmia (VT) [1]. Patients who experience VT will often have implantable cardioverter defibrillators (ICDs), but frequent ICD shocks significantly impact the patient's quality of life.

Radiosurgery has emerged as a novel non-invasive therapeutic modality for treatment of cardiac tachyarrhythmia [2]. Linear accelerators (linacs) deliver therapeutic doses of radiation to targets within a patient's body. Recent works have focused on the ability of linacs to deliver cardiac synchronized radiation doses targeting ventricular tachyarrhythmias [3]. Implantable cardioverter defibrillators (ICD) leads offer a target surrogate that is easily visible in kV imaging and can be assumed to move in approximate synchrony to the radiation target.

The *VERO 4DRT* system is unique in the ability for a radiation beam to move cranio-caudally and laterally to account for motion of the radiation target during treatment [4]. To validate doses delivered in this complex setting, an equally sophisticated quality assurance tool is needed to guide the implementation of new techniques for cardiac radiosurgery.

Commercial phantoms capable of respiratory motion, such as the QUASAR (*Modus QA*) allow for dosimetric validation of respiratory tracking radiotherapy; however, they do not address the issue of coupled cardiac motion. Prior work showed the feasibility of cardiac-lead-based markerless tracking on the VERO4DRT linear accelerator by use of a cardiac motion device in conjunction with the QUASAR respiratory motion phantom to produce simultaneous cardiac and respiratory motions [5]. The phantom was further improved to produce its own respiratory motions, thus removing the dependency on the QUASAR phantom.

The CARP is intended primarily for validation of doses delivered in a setting where cardiac and respiratory motion make target localization more difficult. Furthermore, the CARP system is suited to research the feasibility of markerless tracking of ICD leads moving with simultaneous cardiac and respiratory motion.

II. METHODS

A. Principles of CARP operation

The purpose of this device is to displace a platform in the cranio-caudal and medial-lateral directions – mimicking coupled movement caused by cardiac and respiratory motion. The phantom achieves this by having a two-stage movement system. The first stage consists of a high torque bipolar stepper motor coupled to a lead screw, which drives a piston and scissor lift platform. A scissor lift accommodates an infrared marker block that can be identified and tracked by the medical linear accelerator for respiratory position management. A piston is attached to another platform that moves along a guide rail in the same spatial arrangement (Figure 1).

The second platform accommodates a secondary high-speed and high precision bipolar stepper motor on a rack and pinion system. The rack is mounted onto a linear ball-bearing rail to allow for medial-lateral movement driven by the aforementioned motor. The third and last platform is mounted onto the same rack, and is subjected to both the motion of cardiac and respiratory movements produced by the two motors. This platform is exposed to the radiation field, and is the area of interest in which various dosimeters can be placed.

Both of these motors are driven by a single motor driver shield, and controlled by an Arduino Uno microcontroller. The Arduino Uno (*Arduino*, 2020) microcontroller monitors the limit-switches and sends motion commands to the motor driver board. The Arduino receives user input through a computer, and translates and verifies the instructions before relaying the information to the motors. During start up, the phantom performs a zeroing sequence through the use of limit-switches. These limit-switches also act as hard stops in the event that a motor malfunctions and drives its platform beyond the mechanical limits of the device.

The dominant motion in the device is respiratory motion. Typical organ displacement in an adult human body due to the diaphragm varies from 1.0cm to 3.0cm in the cranio-caudal direction at a rate of 10 – 25 breaths per minute. Cardiac motions range from 0.5cm to 2.5cm in the medial-lateral direction at a range of 5 – 150 beats per minute. The device uses a high-torque stepper motor for the respiratory phase of the device, which assists with the weight from the cardiac motion components, as well as any other load that may be needed during the use of the phantom. The device also uses a high speed and precision stepper motor for the cardiac phase of the device, which helps achieve very fine displacements at both low and high frequencies.

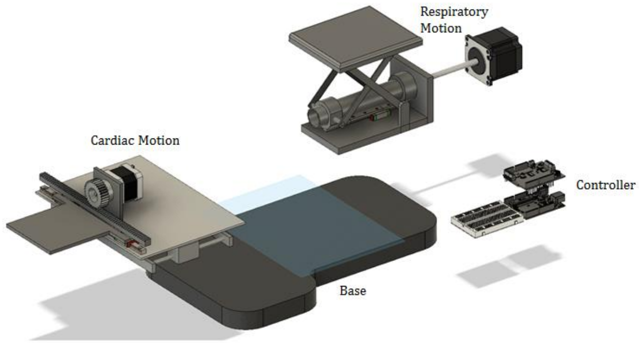

Fig. 1 CARP Schematic

To reduce processing power and prevent stepper motor stuttering, it is ideal to minimize the amount of polling that occurs in the loop() function and eliminate the use of delay() functions. Polling is a technique of acquiring data through continuously sampling or monitoring. However, the CARP is unique in that it was designed to only poll during the rest period for cardiac motion. This allows the microcontroller and motor driver shield to drive each of the stepper motors simultaneously and smoothly. The delay() function is a stop function, and pauses all other processes until the duration of the delay is over. The software circumvents the use of delays through means of using the system clock as a time reference variable; which eliminates the overhead caused by its stop-function counterpart.

The device will not operate without a computer. The program monitors the serial communication line, and waits for input from the user. Once parameters are received, it parses the data into four different variables: respiratory displacement, respiratory breathing rate, cardiac displacement, and cardiac heart rate. The displacement parameters are converted into motor steps and the frequency rates are converted into a velocity (steps per second).

Post conversion, the motors drive each of their respective axes between the zero position, and the set number of steps away from that position (displacement). The time it takes to go from one point to the other, and back is the actual frequency and is automatically adjusted until it matches the user input. Position and velocity feedback are sent through to the serial window, and occurs during the 250 ms break of the cardiac motion.

For the hardware design, it was essential that the irradiation platform was made out of a low Z material to reduce the interference with kilovolt and megavolt x-ray imaging. The other materials were considered strictly by their ability to carry weight while keeping in mind the torque limitations of each motion stage of the device. The other design considerations, such as the limit-switches, were chosen for their ease-of-use, fail-safe mechanism, and ease of replacement.

B. Functional Analysis of the CARP

For each type of motion's displacement, 100 iterations were performed for each of the following displacements: 1mm, 2mm, 3mm, 4mm, 5mm, 10mm, 20mm, 30mm, and max (35mm for cardiac, 40mm for respiratory). These repeatability measurements were made by Bosch GLR225 laser distance reader (Manualslib, 2020) which has an accuracy of 1/32 of an inch (~0.79375mm). Some of the measurements were verified with the Titan 23175 digital caliper (Titan, 2020), which has an accuracy of 0.01mm.

The cardiac and respiratory frequencies were tested through the use of the Tektronix TDS 3014B oscilloscope (Tektronix, 2020). The motions produced by the motors are sinusoidal, so the voltage and current's polarity would flip at each zero crossing. By measuring the time interval in which this change would occur (period), the beats or breaths per minute of the motion can be calculated by:

$$BPM = \frac{1000(milliseconds\ per\ second)}{measured\ period\ (milliseconds)} * 60 seconds\ per\ minute$$

Period measurements are chosen (as opposed to frequency measurements) is because the Arduino Uno microcontroller readily processes time. In order to utilize frequency, it would first be converted to time, which adds additional instructions and processing time for the software.

III. RESULTS

A phantom capable of synchronous user specified respiratory and cardiac motions was created. The required specifications for the CARP were met, as described in table 1.

Table 1 CARP phantom design and function specifications

Specification	Comment
Materials	The irradiation platform is 3D printed with polylactic acid filament. The rest of the device is made out of aluminum and steel
Platform Dimensions	The irradiation platform has a functional field size of 10cm by 10cm
Load	Irradiation platform can carry a load of >5 lbs and does not hinder movement in the cranio-caudal and medial-lateral directions
Respiratory Displacen	The total respiratory travel range is 4cm with a resolution 5.26mm per 200steps 1step = 0.0263mm
Cardiac Displacement	The total cardiac travel range is 3.5cm with a resolution of 44mm per 400steps 1step = 0.11mm
Cardiac Rate	The maximum frequency that the cardiac ste is 250 beats per minute per minute
Respiratory Rate	The maximum frequency that the respiratory stepper motor can achieve is 150 breaths per minute
Simultaneous Motion	Observable; there is no motor stuttering or lag in-between cardiac and respiratory motion.
Operating Voltage	The operating voltage for the Arduino Uno microcontroller is 5VDC, and the operating voltage for the motor driver board is 12VDC with a current limit of 3A
Line Power	An ACDC adapter converts 120VAC to 5VDC and 12VDC with a maximum current output of 4A shared

For CARP motion requirements, repeatability tests showed excellent precision and accuracy in displacement over 100 iterations of the same displacement.

The CARP frequency control tests showed errors <1% over a wide range from 50 to 250 beats per minute, as seen in table 2.

Table 2 CARP frequency control specifications

Programmed bpm	Expected Time (ms)	Measured Period (ms)	Percentage Error
50	12000	12001	0.008%
10	6000	5999	0.017%
20	3000	3000	0.000%
50	1200	1199	0.083%
60	1000	999	0.100%
100	600	600	0.000%
120	500	499	0.200%
160	375	374	0.267%
200	300	299	0.333%
240	250	249	0.400%
250	240	238	0.833%

The phantom was successfully used on the VERO 4DRT system to drive motion of ICD leads for studies in markerless tracking through use of the leads as surrogates. Components used in the design of the phantom did not interfere with kV imaging and the ability of the system to auto-detect ICD leads which were housed on the phantom platform.

IV. CONCLUSIONS

The CARP was designed to satisfy the need of a cardiac-coupled respiratory motion device for research in radiosurgery of cardiac targets.

Hardware design for the CARP satisfied the requirements of minimal interference with kV and MV beams, while key components ensured ease-of-use as well as good precision and accuracy and low component deterioration with use.

For the software design, reduction of latency was key to minimizing motor stuttering and achieving smooth simultaneous motion using only one motor driver shield. Sending serial feedback during the dead-time of the cardiac motion, allowed the microcontroller to focus only on driving the two stepper motors.

Although the current system satisfies the initial design requirements, continual research on other available stepper motors is needed to maximize speed and torque requirements of the device.

Other future development such as mimicking specific patient respiratory and cardiac traces would allow the CARP to be used in the research, development and commissioning of real-time (cardiac & respiratory) gated or target tracking delivery modalities. These modalities would be useful for sites such as ultra-central lung tumors, esophageal tumors and cardiac radiosurgery for the treatment of ventricular tachycardia.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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