Physica Medica xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Physica Medica

journal homepage: http://www.physicamedica.com

Original paper

ADAM: A breathing phantom for lung SBRT quality assurance

Stefania Pallotta [a,b,*], Silvia Calusi [a], Leonardo Foggi [a], Riccardo Lisci [d], Laura Masi [c], Livia Marrazzo [b], Cinzia Talamonti [a,b], Lorenzo Livi [a,e], Gabriele Simontacchi [e]

[a] University of Florence, Department of Biomedical, Experimental and Clinical Sciences "Mario Serio", Florence, Italy
[b] Health Physics Unit AOU Careggi, Florence, Italy
[c] Department of Medical Physics and Radiation Oncology, IFCA, Florence, Italy
[d] University of Florence, Department of Agricultural, Food and Forestry System, Florence, Italy
[e] Radiotherapy Unit AOU Careggi, Florence, Italy

A R T I C L E I N F O

Article history:
Received 29 March 2017
Received in Revised form 6 June 2017
Accepted 4 July 2017
Available online xxxx

Keywords:
Breathing
Phantom
Anthropomorphic
Quality assurance

A B S T R A C T

Purpose: Radiotherapy treatment of moving lesions is a challenging task in which different strategies can be used to adequately treat the tumor while sparing the surrounding tissue. The complexity of these strategies requires accurate and appropriate quality assurance tests. For this purpose, ADAM (Anthropomorphic Dynamic breAthing Model), a new phantom which simulates realistic patient breathing, was developed aiming to test the image quality and dose delivery in lung cancer treatments.
Materials and methods: ADAM reproduces a male torso complete with a moving anterior chest wall and internal parts.

Materials and methods: The phantom's external body is printed with a 3D printer using acrylonitrile butadiene styrene. Internal lungs, ribs, spinal cord, and lung tumor (LT) are made of materials that simulate human tissues. Driven by an Arduino programmable board, the lungs can move along linear or elliptical paths while the anterior chest wall moves up and down. Phantom features and usability, reproducibility of LT position in the phantom chest, internal and external motion repeatability and tumor-to-surface motion correlation were investigated.
Results: Hounsfield Units of the employed materials demonstrates the phantom adequately simulates human tissues. Tests performed with the Synchrony system confirm ADAM's suitability for respiratory internal tracking. Reproducibility of the internal structure position is within 1 mm as are internal and external motion repeatability. A strong positive correlation is found between the lung and chest wall positions ($R^2 = 0.999$).
Conclusions: ADAM demonstrates to be suitable to be employed with gating and tracking devices used in the treatment of moving lesions.

1. Introduction

Radiotherapy treatments of moving lesions is a challenging task that can be carried out with different strategies [1]. Excluding two approaches that simply try to limit the tumor movement (breath holding and forced shallow breathing), three other techniques as motion-encompassing methods, respiratory-gating techniques and tumor-tracking allow treatment during lesion motion but require different dose planning/delivery solutions. In both motion encompassing and respiratory gating techniques, systems able to measure the breathing signal are used during the acquisition of planning 4DCT and, in some cases, also during radiotherapy treatment.

On the contrary, when tumor tracking approaches are chosen, the most challenging task is obviously to detect the tumor position, as the radiation beam must be dynamically repositioned to follow the tumor's changing position.

Several methods have been proposed such as radiographic imaging of the tumor, imaging of fiducial markers implanted near the tumor, or inference of the tumor position from surrogate breathing motion signals. Extensometer devices, such as elastic belts tightened around the patients thorax, or optical systems capturing the light reflected from fiducials or from the patient's body, are employed to acquire the surrogate signals.

It is clear that the complexity of the proposed methods in managing treatment of moving lesions is enormous and a phantom

* Corresponding author at: University of Florence, Department of Biomedical, Experimental and Clinical Sciences "Mario Serio", Florence, Italy.
E-mail address: stefania.pallotta@unifi.it (S. Pallotta).

http://dx.doi.org/10.1016/j.ejmp.2017.07.004

on which to test different treatment strategies has become an indispensable instrument to verify their accuracy. Moreover, considering that these strategies are used in stereotactic body radiation therapies, where high radiation doses are delivered in only a few fractions, the accuracy of the dose delivered to the tumor is even more crucial.

To investigate the accuracy of motion management protocols under conditions as close as possible to clinical situations we developed ADAM (Anthropomorphic Dynamic breAthing Model), a new phantom simulating realistic patient breathing. The phantom and some commissioning tests showing ADAM's performances are here presented.

2. Material and methods

2.1. The phantom

ADAM (Fig. 1) reproduces a male torso endowed with a moving anterior chest wall and internal parts. The internal parts simulate lungs and move along realistic lung lesion paths, while the anterior chest wall moves up and down in sync with internal lungs movement.

No lungs expansion or contraction is realized. The phantom body is printed with a 3D printer using acrylonitrile butadiene styrene (ABS), 30% infill density and a real patient CT as a model. While the external surface (about 60 cm long) is a realistic human body representation, the internal part is realized considering simplified internal organs shapes. In the central phantom region, about 20 cm long and printed with a 100% infill density to obtain a realistic soft tissue approximation [2,3], ribs have been carved and filled with a mixture of calcium sulphate dehydrate. Two blocks, made of cork foils [4], cut and shaped to simulate lungs, are hosted in this region. Inside them, five approximately spherical cavities have been drilled in different pre-defined positions. Four cavities are filled with mouldable bolus (Aquaplast RT Custom Bolus™ Qfix, Avondale, PA, USA) to simulate lung tumors (LT) while the fifth is used to host objects of known dimension and shape, like a fillable sphere (FS) to test the accuracy of 4D scanners in reconstructing moving objects.

The right lung contains two LTs, one in the lung centre and the other close to the lung border, while the left lung contains the FS, one LT with a specific housing for a diamond detector, and the fourth LT surrounded by five small tin markers to test fiducial markers guided tracking procedures. Both lungs were cut along a coronal plane that divides the LTs into two parts, where gafchromic films can be hosted. The lungs can be moved along linear, circular or elliptical paths lying on sagittal planes, while the external chest surface moves independently up and down reproducing realistic thorax movements.

Fig. 1. Picture of external and internal ADAM structure.

2.1.1. Lung and thorax movements

The electro-mechanical apparatus, responsible for lung and thorax movements, is hosted in the caudal phantom region (Fig. 2).

It is fixed to a PMMA slab, which runs underneath the phantom body, and is covered with a thin structure shaped like a realistic abdomen, also printed in ABS, which can be opened.

Anterior-Posterior (AP) and Cranial-Caudal (CC) lungs' movements are driven by five linear actuators (26DBM-L Portescap S. A. Switzerland). Four linear actuators, fixed to the inferior wall of the phantom and connected to a U shaped bar, drive the AP motion component, while a fifth actuator, fixed to the U-bar move an iron plate in the CC direction. Four carbon pipes running through both lungs and connected to the moving iron plate sustain the lungs and transmit the movement. Finally, the thorax movement is carried out by a sixth linear actuator (42DBL-L Portescap) fixed to the inferior wall of the phantom that lifts the anterior phantom chest wall up and down through an iron arm. The phantom is provided with a reset button and bottom courses for linear actuators that ensure that the thorax and lung start positions are always the same. This condition is necessary to have repeatable movements and internal-external correlation.

An Arduino programmable board, completely integrated in the same caudal region, drives the electro-mechanical components that move the lungs and the thorax. The phantom can be connected to a computer using a standard USB port to upload the firmware.

Lungs can move along linear or elliptical paths (simulating hysteresis), with equal inhale and exhale phases or with a shorter inhale than exhale phase (Fig. 3). Lung position along the CC (x) and AP (y) directions are described by the two functions: $x = A \cdot \cos \upsilon$ $y = B \cdot cos(\upsilon + \varphi)$ with A, B and motion amplitudes and phase respectively.

Asymmetrical inhale and exhale breathing cycles are performed by programming actuator velocities to obtain a time-dependent speed. The movement of the thorax y_t, driven by an independent actuator, can be performed in sync, or not, with the lung movement according to the following: $y_t = C \cdot \cos(\upsilon)$ with C thorax motion amplitude. The shape and the extent of the breathing cycle can be changed selecting the desired A, B and C and actuator speed. In the current implementation A, B and C range between 2 mm and 12 mm, while the period (T) ranges between 1.1 and 26 s.

2.2. Tests

ADAM's performances were assessed by evaluating: a) phantom features and usability, b) reproducibility of LT position in the phantom chest, c) internal and external motion repeatability d) tumor-to-surface motion correlation.

2.2.1. Phantom features and usability

A Brillance Big Bore scanner (Philips, Amsterdam, The Netherlands) ($1.17 \times 1.17 \times 1$ mm^3 voxel size) was used to highlight ADAM's internal features while the phantom was still. From the resulting scan, Hounsfield Units (HU) of phantom parts simulating lungs, ribs, LTs and soft tissue regions were measured to verify the approximate equivalence to patient tissues. To fully characterize contrast and visibility of the phantom's internal structures, CBCT and MVCT studies were analyzed. These two studies were acquired with XVI (Elekta AB, Stockholm, Sweden) and TomoTherapy (Accuray Inc., Sunnyvale, CA) systems, respectively.

Please cite this article in press as: Pallotta S et al. ADAM: A breathing phantom for lung SBRT quality assurance. Phys. Med. (2017), http://dx.doi.org/10.1016/j.ejmp.2017.07.004