Physica Medica xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Physica Medica

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

Original paper

Development of a four-dimensional Monte Carlo dose calculation system for real-time tumor-tracking irradiation with a gimbaled X-ray head

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ARTICLE INFO

Article history:
Received 24 October 2016
Received in Revised form 13 January 2017
Accepted 10 February 2017
Available online xxxx

Keywords:
Monte Carlo
4D dose calculation
Real-time tumor-tracking irradiation
SBRT
IMRT

ABSTRACT

Purpose: To develop a four-dimensional (4D) dose calculation system for real-time tumor tracking (RTTT) irradiation by the Vero4DRT.

Methods: First, a 6-MV photon beam delivered by the Vero4DRT was simulated using EGSnrc. A moving phantom position was directly measured by a laser displacement gauge. The pan and tilt angles, monitor units, and the indexing time indicating the phantom position were also extracted from a log file. Next, phase space data at any angle were created from both the log file and particle data under the dynamic multileaf collimator. Irradiation both with and without RTTT, with the phantom moving, were simulated using several treatment field sizes. Each was compared with the corresponding measurement using films. Finally, dose calculation for each computed tomography dataset of 10 respiratory phases with the X-ray head rotated was performed to simulate the RTTT irradiation (4D plan) for lung, liver, and pancreatic cancer patients. Dose-volume histograms of the 4D plan were compared with those calculated on the single reference respiratory phase without the gimbal rotation [three-dimensional (3D) plan].

Results: Differences between the simulated and measured doses were less than 3% for RTTT irradiation in most areas, except the high-dose gradient. For clinical cases, the target coverage in 4D plans was almost identical to that of the 3D plans. However, the doses to organs at risk in the 4D plans varied at intermediate- and low-dose levels.

Conclusions: Our proposed system has acceptable accuracy for RTTT irradiation in the Vero4DRT and is capable of simulating clinical RTTT plans.

1. Introduction

Intrafraction motion, including respiratory motion and the baseline drift of the target, is one of the main concerns in radiotherapy [1]. The general approach to managing such intrafraction motion is to cover the moving target with a large margin at all times throughout the irradiation. However, this method increases the volume of normal tissue that receives undesirable doses [2]. Two solutions to the intrafraction motion are breath-holding irradiation and respiratory-gating irradiation [3]. However, these beam delivery techniques significantly increase the treatment time, thereby compromising patient comfort and consequently increasing the likelihood of patient body movement [4,5]. The ideal method is real-time tumor tracking (RTTT) where the radiation beam is automatically adjusted to follow the tumor's changing position. Recently, several RTTT approaches, such as dynamic multileaf collimator (MLC) tracking [6–8], couch tracking [9,10], and robotic tracking [11,12], have been proposed.

A four-dimensional (4D) image-guided radiotherapy system, Vero4DRT, was developed by Mitsubishi Heavy Industries, Japan (MHI) in collaboration with Kyoto University and the Institute of Biomedical Research and Innovation. The system has a gimbaled X-ray head composed of a compact 6-MV linear accelerator with a C-band klystron-based accelerator, a fixed collimator, and a unique MLC [13]. In addition, electronic portal imaging devices, and two sets of kilo-voltage (kV) X-ray tubes and flat panel detectors acquiring cone-beam computed tomography, as well as fluoroscopy, are mounted on a rigid O-ring shaped gantry. The gimbaled X-ray head, which is one of the unique features of Vero4DRT,

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http://dx.doi.org/10.1016/j.ejmp.2017.02.004

enables its swing function to perform RTTT irradiation for a moving target using real-time imaging and real-time active beam adaptation [13,14].

Previously, we developed and verified specific, high-accuracy Monte Carlo (MC) models of the X-ray head and MLC in step-and-shoot cases for Vero4DRT under non-RTTT conditions [15]. As Vero4DRT swings the gimbaled X-ray head in accordance with a target motion, delivered dose distributions would vary due to changes in the source-surface distance and source-target distance during irradiation. Although it is of clinical importance to verify the dose distributions under RTTT irradiation, no commercial treatment planning systems (TPS) currently support RTTT irradiation cases employing the gimbaled X-ray head.

Hence, the aims of this study were threefold: first, to develop a dedicated dose calculation system for Vero4DRT to calculate the 4D dose distribution using MC simulation; second, to verify 4D dose distribution compared with measurement; and third, to compare isodose curves and dose-volume histograms (DVHs) in clinical RTTT plans with those calculated by single-reference respiratory phase without gimbal rotation.

2. Materials and methods

2.1. Monte Carlo simulation parameters

The EGSnrc/BEAMnrc and EGSnrc/DOSXYZnrc codes [16,17] were used to simulate a 6-MV photon beam delivered from the Vero4DRT system. The detailed geometries of the linac head and MLC were provided by MHI. Each simulation described in the following subsections was performed using parallel processing via a cluster of 2.6 GHz Intel Xeon E5 processors in the supercomputer of the Academic Center for Computing and Media Studies, Kyoto University [18]. The statistical uncertainty in each calculated voxel was within 1% beyond the depth of the maximum dose in the radiation field. The number of incident particles was increased by a factor of 20–50 for the phase space data (PSD) to reduce the statistical uncertainty. The level of PSD recycling was acceptable for all cases because the created PSD was large enough to fully represent the beam fluence and energy. The photon-cutoff energy (PCUT) was set to 0.01 MeV, and the electron-cutoff energy (ECUT) was set to 0.521 MeV for all simulations.

2.2. Dose verification for phantom cases

The following two tests were performed to verify the MC tracking model, employing well-commissioned PSD from the linac head model [15]: (1) a tracking case with a conformal MLC field and (2) a tracking case with a step-and-shoot MLC field.

Similar to the corresponding verification, film measurements were performed using EDR2 films (Kodak, Rochester, NY, USA) and water-equivalent phantoms under the same conditions. Irradiated films were scanned using a flatbed scanner (ES-10000G; Epson Corp., Nagano, Japan), with a resolution of 150 dpi in the 16-bit grayscale, and were analyzed using a DD-System (R-TECH, Tokyo, Japan).

Fig. 1(a) and (b) are A diagram of our MC simulation experiment employing an infrared (IR) camera, QUASAR platform phantom (Modus Medical Devices, London, Ontario, Canada) and a laser displacement gauge (IL-300; Keyence, Osaka, Japan), and a photograph of the experimental setup are shown in Fig. 1(a) and (b), respectively. The QUASAR platform phantom was driven horizontally with the water-equivalent phantom while the IR markers attached to the QUASAR platform phantom moved vertically, and the three-dimensional (3D) positions of the IR markers were transferred to Vero4DRT. Next, the gimbaled X-ray head adjusted its orientation by rotating around two orthogonal axes (pan or tilt rotations). The definitions of the pan and tilt rotations are shown elsewhere [19]. Pan refers to lateral angles, and tilt refers to longitudinal angles. The tracked PSD position (x', y', z') was calculated as follows:

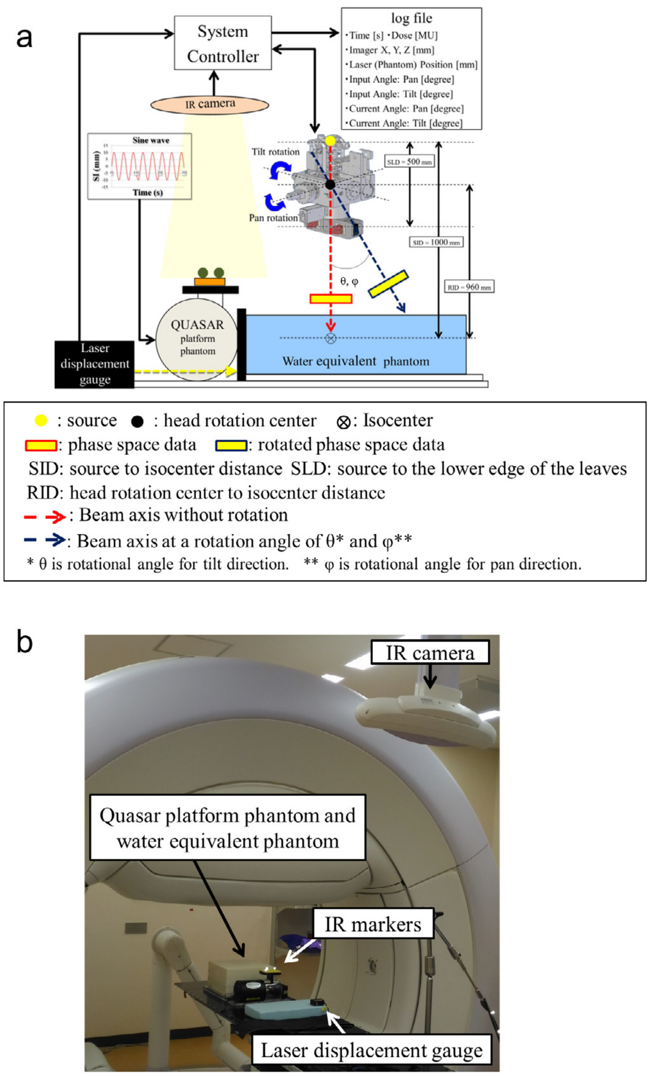

Fig. 1. (a) Geometric scheme of the tilt rotational angle θ and pan rotational angle φ in the Vero4DRT system. (b) A photograph of the experimental setup.

$$\begin{pmatrix} x' \\ y' \\ z' \\ 1 \end{pmatrix} = \begin{pmatrix} \cos\varphi\cos\theta & -\sin\varphi & \cos\varphi\sin\theta & 0 \\ \sin\varphi\cos\theta & \cos\varphi & \sin\varphi\sin\theta & 0 \\ -\sin\theta & 0 & \cos\theta & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix} \quad (1)$$

where x, y, and z are the current PSD positions along the left-right (LR), anterior-posterior (AP), and superior-inferior (SI) directions. The tilt and pan angles were expressed as θ and φ, respectively.

During beam delivery, the horizontal displacement of the QUASAR platform phantom was measured directly by the laser displacement gauge at a frequency of 100 Hz. The pan and tilt angles and MUs, as well as the indexing time indicating the phantom position, were also extracted from a log file to calculate the doses at the corresponding positions.

2.2.1. Verification of the calculated dose to the measured dose

First, the QUASAR platform phantom was driven at a frequency of 0.25 Hz with an amplitude of 15 mm in the SI direction, while

Please cite this article in press as: Ishihara Y et al. Development of a four-dimensional Monte Carlo dose calculation system for real-time tumor-tracking irradiation with a gimbaled X-ray head. Phys. Med. (2017), http://dx.doi.org/10.1016/j.ejmp.2017.02.004