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Technical note

4D modeling in a gimbaled linear accelerator by using gold anchor markers

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ABSTRACT

Purpose: The purpose of this study was to verify whether the dynamic tumor tracking (DTT) feature of a Vero4DRT system performs with 10-mm-long and 0.28 mm diameter gold anchor markers.

Methods: Gold anchor markers with a length of 10 mm and a diameter of 0.28 mm were used. Gold anchor markers were injected with short and long types into bolus material. These markers were sandwiched by a Tough Water (TW) phantom in the bolus material. For the investigation of 4-dimensional (4D) modeling feasibility under various phantom thicknesses, the TW phantom was added at 2 cm intervals (in upper and lower each by 1 cm). A programmable respiratory motion table was used to simulate breathing-induced organ motion, with an amplitude of 30 mm and a breathing cycle of 3 s. X-ray imaging parameters of 80 kV and 125 kV (320 mA and 5 ms) were used. The least detection error of the fiducial marker was defined as the 4D-modeling limitation.

Results: The 4D modeling process was attempted using short and long marker types and its limitation with the short and long types was with phantom thicknesses of 6 and 10 cm at 80 kV and 125 kV, respectively. However, the loss in detectability of the gold anchor because of 4D-modeling errors was found to be approximately 6% (2/31) with a phantom thickness of 2 cm under 125 kV. 4D-modeling could be performed except under the described conditions.

Conclusions: This work showed that a 10-mm-long gold anchor marker in short and long types can be used with DTT for short water equivalent path length site, such as lung cancer patients, in the Vero4DRT system.

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1. Introduction

Respiratory tumor motion management is one of the most important issues in radiotherapy, especially in the case of thoracic and abdominal tumors.[1] Various methods have been proposed to reduce the impact of respiratory-induced tumor motion during beam delivery. The dynamic tumor tracking (DTT) technique with a gimbal-mounted linac for respiratory-induced tumor motion compensation is capable of tracking the three-dimensional (3D) position of a fiducial marker based on four-dimensional (4D) modeling.[2–4] The Vero4DRT system is in clinical use for respiratory-induced organ motion, such as in the lung, liver, and pancreas. Doses to the planning target volume (PTV) and to organs at risk (OARs) in DTT have been shown to be 30–35% and 20–30% lower than those in conventional motion encompassing methods.[4] Matsuo et al. summarized procedures, the quantify tracking error, tumor-fiducial uncertainties, and PTV margins for DTT at the Kyoto University (KU, Kyoto, Japan), Institute of Biomedical Research and Innovation (IBRI, Kobe, Japan) and UZ Brussel (UZB, Brussels, Belgium). The Vero4DRT system for DTT uses kilo-voltage (kV) X-rays for target localization, but in soft tissues it is not possible to visualize the target on the kV X-ray images. The Vero4DRT system performs DTT using fiducial markers, made of high-Z materials, such as gold, near or in the target. KU-IBRI implanted three or more 1.5 mm spherical gold markers around the tumors using a bronchoscope. UZB inserted a cylindrical 0.75 mm diameter gold marker inside or close to the tumor percutaneously.[3] 0.75 mm diameter Visicoil marker was used in its first clinical application for the treatment of a patient with liver cancer in our institution. Larger fiducial markers need to be inserted with large diameter needles that cause pain. In addition, the presence of metal may influence the dose distribution.[5]

A 0.5%-iron-containing fiducial marker has been shown to be useful in an image registration and bleeding and pain can be avoided by the use of a thin needle.[6] 4D modeling is achieved by detecting the implanted fiducial markers in kV X-ray images acquired before treatment. These implanted fiducial markers require high image contrast for accurate target position information because 4D modeling fails under poor or ambiguous imaging conditions. The physical characteristics of the gold markers strongly depend on their length and diameter.[7–9] The Vero4DRT system for clinical use must anticipate the possibility that detection by the marker or the 4D-modeling may fail. To the best of our knowledge, gold anchor markers have not been reported for use in 4D modeling in the Vero4DRT system.

The purpose of the current study was to verify whether the DTT feature of the Vero4DRT system performs with a gold anchor marker. The feasibility of the gold anchor marker under various phantom thicknesses was investigated using 4D modeling. The detectability loss of the gold anchor marker was quantified, and the limitation of 4D modeling was investigated.

2. Materials and methods

The Vero4DRT system (Mitsubishi Heavy Industries, Ltd., Tokyo, Japan, and Brainlab, Feldkichen, Germany) was used in this work. Mechanical details of the Vero4DRT system have been described elsewhere.[10–15] In brief, DTT is based on the correlation between the internal tumor position and external surrogated infrared (IR) markers. This is known as 4D modeling. The 3D positions of the internal target are provided via an implanted fiducial marker detected with the kV X-ray imaging subsystems. These orthogonal systems are attached to the O-ring at 45° from the mega voltage (MV) beam axis. The gimbal swinging pursues the target in real time for organ motion compensation of the treatment beam along two orthogonal directions (pan and tilt) up to ±2.5°, based on 4D modeling. Two types of fiducial markers are available with the Vero4DRT system: a spherical (short type) and cylindrical (long type) marker. The gold anchor marker had a winding, zigzag shape that could be bent into a spherical shape. Gold anchor markers with a length of 10 mm and a diameter of 0.28 mm were used in this study. They were injected into bolus material (10 cm × 10 cm × 2 cm) with short and long types as shown in Fig. 1. These markers were pieces of gold wire that folded and collapsed during implantation under the pressure of the soft surrounding tissues. They were implanted according to the manufacturer's instructions with prepared application needles and were sandwiched by a Tough Water (TW) phantom (Kyoto Kagaku Co., Ltd., Kyoto, Japan). For the investigation of 4D modeling feasibility under various phantom thicknesses, the TW phantom was added at 2 cm intervals (in upper and lower each by 1 cm).

All markers were scanned with a computed tomography (CT) system (Optima CT 580W; GE Healthcare, Milwaukee, WI). Single-energy CT images were acquired according to standardized treatment-planning body protocol with 120 kV, 400 mA s, a 500 mm field of view (FOV), and slice thickness of 1.25 mm. The transversal pixel resolution was 0.977 mm. The CT scans were transferred to an iPlan RT Dose treatment planning system (TPS) version 4.5.3 (Brainlab AG, Feldkirchen, Germany). The virtual target was created by delineating the contour of the CT images for plan design. This plan was transferred to the Vero4DRT and ExacTrac systems (BrainLAB AG, Feldkirchen, Germany), and the implanted marker was defined by the planning CT on the ExacTrac system.

Fig. 2 shows a diagram of the experimental setup for investigating the feasibility of 4D-modeling. The programmable dynamic phantom (CIRS Inc., Norfolk, VA, USA), capable of producing motion based on an arbitrary input function, was used to simulate breathing-induced organ motion synchronously with a respiratory surrogate. This dynamic phantom had two tables: one that moved in the horizontal direction and one that moved in the vertical direction. The TW phantom with the fiducial markers was placed on the horizontal table. The phantom with five IR markers was placed on the vertical table to acquire a breathing signal. A sinusoidal motion wave sequence was produced in the dynamic phantom, using different amplitudes and breathing periods. The amplitude of the IR marker motion was fixed at 20 mm. A 3 s cycle was evaluated when the