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Cone beam CT

Acquisition of MV-scatter-free kilovoltage CBCT images during RapidArc™ or VMAT

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Purpose: To perform kilovoltage (kV) cone beam computed tomography (CBCT) imaging concomitant with the delivery of megavoltage (MV) RapidArc treatment, and demonstrate the feasibility of obtaining MV-scatter-free kV CBCT images.

Methods and materials: RapidArc/CBCT treatment and imaging plans are designed, and delivered on the Varian TrueBeam, using its Developer Mode. The plan contains 250 control points for MV-radiation delivery, each over an arc of 0.4–0.7°. Interlaced between successive MV delivery control points are imaging control points, each over an arc of 0.7–1.1°. During the 360° gantry rotation for the RapidArc delivery, CBCT projections of a phantom are acquired at 11 frames per second. The kV projections with minimal MV-scatter are selected, based on gantry angle, and the $CBCT_s$ image reconstructed. For comparison, a reference $CBCT_r$ image is acquired in the normal way. In addition, to examine the effect of MV-scatter we acquire $CBCT_c$ using the same treatment plan without the imaging control points, i.e. with continuous MV delivery during the 360° rotation. Quantitative evaluation of image qualities is performed based on the concepts of CNR (contrast-to-noise ratio) and NSTD (normalized standard deviation).

Results: The different types of CBCT images were reconstructed, evaluated, and compared. Visual comparison indicates that the image quality of $CBCT_s$ is similar to that of the reference $CBCT_r$, and that the quality of $CBCT_c$ is significantly degraded by the MV-scatter. Quantitative evaluation of the image quality indicates that MV-scatter significantly decreases the CNR of CBCT (from ~7 to ~3.5 in one comparison). Similarly, MV-scatter significantly increases the inhomogeneity of image intensity, e.g. from ~0.03 to ~0.06 in one comparison.

Conclusion: We have developed a method to acquire MV-scatter-free kV CBCT images concomitant with the delivery of RapidArc treatment. Engineering development is necessary to improve the process, e.g. by synchronization of the MV and kV beams.

The evolution of technologies for image guided radiation therapy (IGRT) has been rapid over the last two decades [2,8,11]. The introduction of electronic portal imaging devices in the early 1990s, enabling digital portal imaging, was an important step in modern IGRT. More recently, kilovoltage cone beam computed tomographic imaging devices (CBCT) capable of generating 3D images of soft tissues have been incorporated into radiation treatment devices, ushering in a new era of IGRT [2,8,11]. There are numerous examples describing the use of CBCT in clinical radiotherapy, including set up, monitor, or track the patient and/or tumor positions during treatment [22].

Importantly, CBCT facilitates the realization of adaptive radiotherapy [23]. For example, the CBCT data taken with the patient on the treatment couch can be compared to the planning CT images for verifying the geometrical accuracy of the radiation treatment. For dosimetric evaluation, the treatment CBCT can be overlaid with isodose distributions of the original plan, or with the "delivered" dose distribution calculated using the trajectory logs of treatment delivery [10]. These images and/or dosimetric comparisons may be used for re-planning when there is a significant deviation between the planning and treatment of CT images, or between the planned and delivered dose distributions, in accordance to the concept of adaptive radiotherapy [19].

However, at present, the CBCT images are acquired either before or after radiation delivery. A number of studies have reported on the intra-fraction changes in target position during a radiotherapy session, which generally increase with the duration of the treatment delivery time [1,4–6]. An implication of the results from these studies is that adaptive therapy based on CBCT images is subject to 'residual' uncertainties resulting from intra-fraction organ motion. Thus, ideally CBCT images should be obtained concomitantly with radiation delivery.

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There is increasing enthusiasm for the use of volumetric modulated arc therapy (VMAT) or RapidArc in administering intensity-modulated radiotherapy (IMRT) [9,14].[2] Studies have indicated that VMAT not only produces highly conformal dose distributions, similar to those of other forms of IMRT, but that it requires less MU and can be delivered in a shorter treatment time [9,14]. Relative to the intra-fraction 'residual' uncertainties, the shorter treatment time of RapidArc is beneficial. Important for the present study, the use of a 360° gantry rotation in many RapidArc treatment plans avails the possibility of performing CBCT image acquisition during actual radiation delivery, although a 360° gantry rotation is not a requirement for CBCT or RapidArc.

CBCT images acquired concomitantly with radiation treatment delivery may be negatively affected by the scatter from the MV beam [12,13,21]. In this investigation, we devised a method to obtain CBCT images with nearly zero or minimal MV-scatter, and performed proof-of-principle studies to demonstrate such capabilities.

Materials and methods

The treatment planning and delivery of RapidArc are based on the concept of control points (CPs) [14]. To achieve conformal dose distribution, variable dose-rate, variable gantry speed, dynamic MLC movements are included in the optimization and delivery of radiation in each of the CPs. In the implementations of both Varian's RapidArc, and VMAT at Memorial Sloan Kettering Cancer Center, 177 CPs are used, equi-spaced over a 360° gantry rotation [14,24]. To perform CBCT acquisition, concomitant with RapidArc delivery, we propose dividing each CP into two, with the first for MV-radiation delivery and the second for acquiring kV projections. During the imaging CP, the MV-radiation beam is turned off to exclude MV-scatter in the kV projection images. However, this method requires the synchronization between the processes for MV-radiation delivery and kV image acquisition, which is at present not possible in the linac systems available to us. Nevertheless, in this study we designed experiments to demonstrate in proof-of-principle that CBCT images with negligible or near-zero MV-scatter can be acquired concomitantly with RapidArc delivery.

The use of the Developer Mode of the Varian TrueBeam

In the Developer Mode, the Varian TrueBeam uses the same control system as in the Clinical Modes, but enables access to additional advanced control features. Specifically, in the Developer Mode, the TrueBeam system is driven by XML (extensible markup language) beams loaded into the control console workstation computer. XML beams are essentially text scripts in XML format in which a rich instruction set allows Developer Mode users to construct and implement complex non-standard beams and imaging processes. In this study, the ability of the Developer Mode to load and implement user-designed XML beams and imaging processes is key to performing the experiments to acquire MV-scatter-free CBCT images, as described below.

Experimental design for simultaneous RapidArc delivery and CBCT acquisition

The number of MV and kV control points

To demonstrate simultaneous RapidArc delivery and CBCT acquisition we designed plans using 250 MV-radiation delivery CPs, interlaced with 249 kV imaging CPs, such that each pair of MV + kV CPs corresponds to an average gantry angle of 1.44°, for a total gantry rotation of 357.8°. This choice is in part constrained by the Varian TrueBeam which limits the total number of CPs to be 500 or less. In the future, increasing the imaging CPs may be beneficial to improve the quality of the CBCT images.

MV-radiation delivery

10 MV photon beams was used during the 250 MV-radiation delivery CPs. In the first set of experiments, a fixed 10 × 10 cm field was used with 250 MU. The MV delivery was over a gantry angle of 0.4°, and the imaging CP over 1.0° or 1.1° (due to the 0.1° constraint in gantry angle setting). In the second set of experiments, to simulate clinical situations at MSKCC, a 325 MU VMAT plan for the treatment of a prostate tumor was used [24]. In this case, the MV delivery was over a gantry angle of 0.7°, and the imaging CP over 0.7° or 0.8°. The MV delivery CP was over a wider gantry angle because of the longer time needed for intensity modulated beams.

During each of the imaging CP, we specified the delivery of 0.01 MU. This, in addition to the specification of gantry speed (see below), was necessary to avoid uneven gantry rotation speed during the treatment and imaging control points, respectively.[3] Although MV-scatter (from the 0.01 MU per imaging CP) will attend the CBCT projection images, the magnitude of this MV-scatter is ⩽1% of that from the 250 and 325 MU RapidArc delivery over ~360° gantry rotation. Nevertheless, the term "MV-scatter free CBCT" in this report should be regarded with this qualification. Also, although this requirement (of 0.01 MU for each imaging CP) is needed for the present proof-of-principle study, it will be unnecessary in future clinical implementation with the engineering improvements as described in the "Discussion" section.

Acquisition of CBCT image during RapidArc

kV CBCT projections were continuously acquired during gantry rotation at a frequency of 11 frames/s. The imaging parameters were as follows: half-fan geometry, 125 kVp, 80 mA, 13 ms exposures, with 2 mm slice thickness, and reconstructed into a 512 × 512 × 80 voxel array. The Phantomlab Catphan 504 phantom[4] with elliptical expansion was placed at the isocenter. The phantom has inserts of materials with different densities (polystyrene, acrylic, Delrin, Teflon, Air, and polymethylpentene, polyethylene etc.), and is ideal for evaluation of CBCT image quality. The elliptical expansion measures 38 × 30 × 20 cm in the lateral, AP-PA and vertical dimensions, and is a reasonable simulation of the pelvis of a patient.

To ensure that sufficient number of MV-scatter free CBCT projections were acquired within the imaging CP, we set the maximum gantry speed at 2.7°/s for the 250 MU (10 × 10 cm) delivery, and 2.2°/s for the 325 MU RapidArc delivery. This experimental design ensures near-uniform gantry speed over the 360° rotation for both plans. In the implementation on the TrueBeam, ~2.1 min was needed for the 250 MU (10 × 10 cm) plan, and ~2.7 min for the 325 MU RapidArc plan, respectively.

Analysis and comparison of CBCT images

Standard CBCT image of Catphan 504

As a basis for comparison we obtained a standard or reference CBCT image, i.e. with kV imaging only, using the manufacturer's pelvis imaging protocol, i.e. half-fan geometry, 125 kVp, 80 mA, 13 ms, 660 projections for a total of 680 mAs, reconstructed at

[2] In this paper, the terms VMAT and RapidArc are used interchangeably.

[3] In Varian's design of RapidArc, to increase the rapidity of treatment, the linac operates at either maximum gantry speed or maximum dose rate. At the entry and exit of a zero dose segment, gantry rotation is momentarily stopped. To prevent the stop-and-go at the entry and exit of a zero dose segment, we specify 0.01 MU for each imaging CP.

[4] For a detailed description, go to http://www.phantomlab.com.