An evaluation of cine-mode 3D portal image dosimetry for Volumetric Modulated Arc Therapy

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Abstract: We investigated cine-mode portal imaging on a Varian Trilogy accelerator and found that the linearity and other dosimetric properties are sufficient for 3D dose reconstruction as used in patient-specific quality assurance for VMAT (RapidArc) treatments. We also evaluated the gantry angle label in the portal image file header as a surrogate for the true imaged angle. The precision is only just adequate for the 3D evaluation method chosen, as discrepancies of 2° were observed.

1. Introduction
The Electronic Portal Image dosimeter (EPID) has become a standard tool for evaluation of complex radiation treatments [1]. The most common configuration has been as an integrating dosimeter, but more recently, cine-mode acquisition has become viable. This mode provides a potentially useful tool for Volumetric Modulated Arc Therapy (VMAT), a novel treatment modality that involves simultaneous modulation of dose rate, field apertures and gantry speed.

Although the integrating mode has been adapted for VMAT dosimetry [2] the so-called “collapsed” 2D distribution is considered less useful than in conventional IMRT because the angular information is entirely absent, even if the gantry is rotated during acquisition. Cine acquisition opens up the possibility of true 3D dose reconstruction, as in a method recently developed by Mans et al. [3] for transmission dosimetry using the Elekta VMAT delivery and imaging system.

Cine mode presents some significant dosimetric challenges; Varian’s IAS2 system, for example, has an unacceptably long dead-time [4]. McCurdy and Greer [5] performed the first definitive study of the current IAS3 system. Their study was limited to single frame images and dose rates that were varied by changing the nominal monitor unit (MU) rate. They discovered a deficiency of 1-2 frames per acquisition and speculated that this occurred at the end of irradiation. Beyond dosimetry, the accurate recording of the gantry angle during each image acquisition is also a major concern.

In this work we first evaluated Varian’s IAS3 cine mode acquisition, paying particular attention to dose rate linearity and accuracy of the gantry angle recorded in the Dicom header of each image (the “header angle”). We then used this mode to deliver VMAT (RapidArc) plans for head & neck treatments, and evaluated them using an adaptation of a 3D virtual-phantom reconstruction technique that has proven very successful in 3D IMRT QA [6]. In this new technique, “Camera” (Composite Acquisition Method for Evaluating Radiotherapy Arcs), the header angle is a critical element because it enables the acquisition process to be self-contained. We show that Camera provides a rapid and robust method for determining whether the dose is out of tolerance compared to a calculated 3D distribution in a cylindrical phantom.
and examples of successful and incorrect treatment deliveries are discussed. We also present data that suggests that 2D techniques may be inadequate to detect these incorrect deliveries.

2. Methods and Materials

All radiation deliveries were performed on a Varian Trilogy linear accelerator at the Vancouver Centre using a beam energy of 6MV.

2.1. Dosimetric linearity.

Linearity checks were performed at the nominal rate of 600MU/min, which is the mode used exclusively in RapidArc delivery. The actual MU rate was varied by changing the MU per degree, as in clinical operation, where the gantry rotation rate is limited to a maximum of 4.8°/s. Effective MU rates of 80 to 600MU/min were investigated, using 3 to 12 frames per image at an acquisition rate of about 12 frames/s.

2.2. Angular precision.

A “radiographic inclinometer” (Figure 1) was constructed that allowed comparison of the header angle to the actual start and stop angles of each image acquisition. It consisted of a pair of lead-solder wires wound in an open spiral around a 20cm long, 13cm diameter acrylic tube, coaxial with the gantry rotation axis. As the gantry rotated, the apparent intersection point of the wires moved proportionally along the axis. Cine sequences of up to 12 frames per image were recorded. The number of frames was limited by the blurring of the wire, to the point where the start and end points of the acquisition could not be determined. The inclinometer was designed to resolve the dead frame effect [5]. To achieve the required high spatial resolution, the inclinometer covered a range of only 40°; and it was calibrated with static fields 5° apart over that range.

We also delivered conformal arcs up to 360° (where the dose and gantry rotation rates are assumed to be constant), without the inclinometer in place. We made use of the constant frame acquisition rate, at 6 to 12 frames per image, to estimate the accuracy of the header angles.

2.3. RapidArc plan evaluation with Camera

Representative clinical dose distributions were optimized in RapidArc (Eclipse 8.6.17, Varian Medical Systems). These were converted to verification plans on a 20.4 cm diameter phantom and delivered with 6 to 12-frame cine imaging enabled, corresponding to 2-5° per image. Camera uses the same method of registration and calibration as its predecessor [6]; but for consistency with the arc acquisitions, the 10x10cm² calibration and flood fields were also acquired in cine mode.

The ability to validate patient plans and discriminate against invalid delivery or incorrect plans is based on χ−scores [7], with a dose/distance-to-agreement tolerance of 3%/3mm. This metric is evaluated within a high-dose volume (dose above 80% of the prescription) approximating the PTVs, and an intermediate dose volume (40-80%) representing the critical organ locations.

Some RapidArc plans were transformed into conformal arc deliveries with the same MLC apertures and the same total MU, but without dose rate or gantry speed variations, and these served as the incorrectly-delivered plans.

The cine images were also summed to represent integrated images. These were compared in 2D with “collapsed” verification plans at gantry angle 0°, in a plane normal to the beam axis.

3. Results

3.1. Dosimetry

Relative dose measurements reproduced the frame deficiency [5], and showed that it was independent of both the actual dose rate and MU delivered. The EPID signal was independent of frames per image to better than 1.5%, when the missing frames were accounted for. There was a small signal loss compared to the normal integrating mode, but all measurements for Camera were performed in cine mode so this effect was not investigated further.
3.2. Angular precision

The inclinometer calibration was approximately 10 pixels/degree in the vertical image direction, with the exact scale being dependent on source to imager distance. The linearity and resolution was about ±0.1° and showed that the 1.5-2 frame deficiency occurred during the final image, where acquisition terminated prematurely about 1° before the actual end of an arc delivery (In Figure 2, the gantry rotated from 2° to 34°). This effect was independent of the number of frames and dose rate. By comparing successive stop and start angles, it appeared that there was no dead time between images, for up to 12 frames per image.

The phase relationship between the header angle and the start or end of image acquisition was found to be rather complex. It is on average closer to the mid-point of the acquisition than either the start or end (mean difference ±0.9°); however the variation is significant (σ = 0.6°) and depends on the acquisition rate. The phase lags during 3-frame acquisition but tends to advance for 12 frames; and, from the number of repeated header angle instances, it seems that the angle may be updated in the Varian “4D-treat” application no more than 2-3 times per second.

Over the 360° range where the gantry rotation rate was assumed to be constant, we found that the header angle increment can vary by several degrees from its nominal value, (σ = 1°) and again, in several instances the increment was zero – i.e., the same angle appears in successive images.

3.3. Summary of Camera validations

Figure 3 shows one plan (a) delivered according to expectations, and one (b) delivered as a conformal arc so that the total MU and isocentric dose was correct, but the angular distribution was not. The χ-scores for case a) were 84% and 96% of points within tolerance for the high- and low-dose volumes respectively, while for case b) the corresponding scores were only 55% and 57%. Visual inspection confirmed the expected “hourglass”-shaped regions of discrepancy. Our previous experience with 3D IMRT validation (nearly 500 plans) has shown that an 80% score is a valid minimum pass criterion.

The integrating-mode comparisons with “collapsed” verification plans, which also used the χ metric in 2D, were unable to differentiate between the correct and incorrect treatment deliveries.

4. Discussion and Conclusion

We confirmed that Varian’s cine mode is sufficiently linear during a typical VMAT delivery for EPID dosimetry to be viable. We identified issues with the EPID header angle that may confine its use to specific applications where these limitations have been properly assessed. Within Camera 3D
verification, the header angle has been defined as mid-way through the image acquisition, although it is known to vary by up to 2° from this point. The cause is currently unknown but may be due to communication limitations between the linac controller and the treatment workstation, or even within the treatment/acquisition application itself. We are exploring this issue in more detail with real-time measurement of gantry angle during arc delivery, using a gantry-mounted inclinometer.

Given the limited precision of the header angle, we have shown that the maximum useful acquisition rate is about one image per 3-4° of gantry rotation, or about 10 frames (just under 1 s) per image. For the virtual phantom used in the initial version of Camera, this translates to a positional resolution at the cylinder surface of about 6 mm. As this is more than two pixels at the calculated dose resolution of 2.5 mm, higher angular precision would definitely be an advantage. Nevertheless, the current technology appears sufficiently accurate to detect clinically-significant 3D dose discrepancies in RapidArc deliveries where the high-dose volume is less than about 20 cm in diameter.

Finally, by synthesizing integrated images, we were able to demonstrate that 2D QA methods would probably not have been able to detect the delivery errors that were introduced.

Acknowledgement
Partial funding for this work was provided by Varian Medical Systems.

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