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Beam Hardening Effects on IMRT QA

Jinsheng Li, Ph.D and Yihang Xu, PhD
Radiation Oncology, University of Miami Miller School of Medicine

ABSTRACT

Purpose: Electronic portal imaging device (EPID)-based portal dosimetry is widely used for patient-specific quality assurance (PSQA) of intensity-modulated radiation therapy (IMRT) and volumetric modulated arc therapy (VMAT). Because amorphous silicon EPIDs exhibit an energy-dependent response and multi-leaf collimator (MLC) transmission produces a hardened photon spectrum, differences may exist between MLC parameters measured with an ionization chamber (IC) and those measured with an EPID. This study investigated the impact of detector-dependent MLC transmission and dosimetric leaf gap (DLG) measurements on portal dosimetry for IMRT and VMAT quality assurance.
Methods: MLC leaf transmission and DLG were measured using an IC and an EPID for 6 MV, 6 MV flattening filter-free (6FFF), 10 MV, 10FFF, and 15 MV photon beams from a Varian Edge linear accelerator. Separate treatment planning system (TPS) beam models were commissioned using the IC- and EPID-measured MLC parameters. Single-target and three-target stereotactic radiosurgery (SRS) plans and TG-119 VMAT verification plans were generated and verified using EPID portal dosimetry. Gamma passing rates obtained with the two commissioning approaches were compared.
Results: Significant differences were observed between the IC- and EPID-measured MLC transmission and DLG values, with the largest discrepancies occurring for the flattening filter-free beams. For the 6FFF beam, the measured MLC transmission decreased from 1.06% with the IC to 0.59% with the EPID, reflecting the energy-dependent response of the EPID to the hardened MLC-transmitted photon spectrum. TPS beam models commissioned with EPID-measured transmission and DLG values produced consistently higher gamma passing rates for both SRS and TG-119 VMAT plans than those commissioned with IC-measured values. The improvement was most pronounced for flattening filter-free beams, with multiple treatment plans demonstrating clinically meaningful increases in gamma passing rates.
Conclusions: The energy-dependent response of the EPID significantly influences portal dosimetry for IMRT and VMAT quality assurance. Detector-specific MLC transmission and DLG values should be incorporated into TPS beam models used for portal dose prediction to improve agreement between calculated and measured portal dose distributions. In contrast, ionization chamber-based commissioning parameters should continue to be used for patient dose calculation to ensure accurate absorbed-dose estimation in medium.

CONTACT

Jinsheng Li, Ph.D.
Department of Radiation Oncology, University of Miami Miller School of Medicine
2111 Sole Mia Way; N Miami, FL 33181

jxl3752@miami.edu
786 392 6365

INTRODUCTION

Intensity-modulated radiation therapy (IMRT) and volumetric modulated arc therapy (VMAT) are widely used in modern radiation therapy to achieve highly conformal dose distributions while minimizing dose to adjacent normal tissues. A key component of both techniques is the multi-leaf collimator (MLC), which dynamically shapes the treatment aperture and modulates beam fluence throughout dose delivery. Consequently, accurate commissioning and validation of IMRT/VMAT dose calculation and delivery are essential to ensure treatment accuracy.
Patient-specific quality assurance (PSQA) is routinely performed to evaluate the agreement between treatment planning system (TPS)-calculated and measured dose distributions for representative or patient-specific treatment plans. Various dosimetric systems are used for PSQA, including ionization chambers, diode arrays, radiochromic film, and electronic portal imaging devices (EPIDs). Among these, EPID-based portal dosimetry offers high spatial resolution, rapid image acquisition, and an efficient clinical workflow for planar dose verification. Previous studies have shown that amorphous silicon EPIDs exhibit an energy-dependent response. Beam transmission through the MLC hardens the photon spectrum, resulting in a higher average photon energy than that of the open beam. Because IMRT and VMAT involve extensive MLC modulation and complex delivery patterns, the dosimetric impact of beam hardening and detector energy dependence may influence PSQA accuracy and gamma passing rates. Therefore, measurement-based QA remains an essential component of clinical practice. In this study, we investigated the impact of MLC-induced beam hardening and detector energy dependence on IMRT patient-specific quality assurance.

METHODS AND MATERIALS

MLC Transmission and Dosimetric Leaf Gap Measurements
MLC leaf transmission and dosimetric leaf gap (DLG) were measured using an ionization chamber (IC) and an electronic portal imaging device (EPID), respectively, for all photon beam energies available on an Edge linear accelerator (Varian Medical Systems, Palo Alto, CA, USA), including 6 MV, 6 MV flattening filter-free (6FFF), 10 MV, 10FFF, and 15 MV. Measurements were performed using the moving-gap method recommended by the manufacturer. The measured MLC transmission and DLG values obtained with the IC and EPID were separately used to commission the treatment planning system (Eclipse v18.1, Varian Medical Systems), resulting in two detector-specific beam models for each photon energy.

Treatment Plan Quality Assurance
Following commissioning of the linear accelerator and TPS, stereotactic radiosurgery (SRS) treatment plans with single-target and three-target geometries, as well as TG-119 VMAT verification plans for the prostate, head-and-neck, and C-shaped targets, were generated on a solid-water phantom for all photon beam energies. Each SRS plan consisted of four coplanar arcs, whereas each TG-119 VMAT plan consisted of two coplanar arcs.
For each treatment plan, dose calculations were performed using the TPS commissioned with either the IC- or EPID-measured MLC transmission and DLG values. Portal dosimetry measurements were acquired using the EPID for all plans. Gamma analysis was performed on an arc-by-arc basis. Gamma passing rates were evaluated using criteria of 3%/1 mm and 1%/1 mm for the SRS plans, and 2%/2 mm and 1%/1 mm for the TG-119 VMAT plans.

RESULTS

The measured MLC leaf transmission and dosimetric leaf gap (DLG) values obtained with the EPID and ionization chamber (IC) are summarized in **Table 1** for all photon beam energies of the Edge linear accelerator. Differences were observed between the IC- and EPID-measured values for both MLC transmission and DLG, with the largest discrepancies occurring for the flattening filter-free (FFF) photon beams.
Gamma passing rates for the stereotactic radiosurgery (SRS) treatment plans are presented in **Table 2** for the treatment planning system (TPS) commissioned with the IC-measured MLC transmission and DLG values, and in **Table 3** for the TPS commissioned with the EPID-measured values. Compared with the IC-based beam model, the EPID-based beam model demonstrated improved gamma passing rates for several SRS plans. Improvements of 5% or greater are highlighted in green in **Table 3**.
The gamma passing rates for the TG-119 VMAT verification plans are summarized in **Table 4**, which compares the results obtained using TPS beam models commissioned with the IC- and EPID-measured MLC transmission and DLG values. Similar to the SRS results, several TG-119 plans showed improvements in gamma passing rates when the EPID-based commissioning parameters were used. Improvements of 5% or greater are highlighted in green in **Table 4**.

Table 1. Comparison of the measured transmission and DLG with IC and EPID.

	Leaf Transmission (%)		DLG (mm)	
Beams	Ion Chamber	EPID	Ion Chamber	EPID
6MV	1.24	1.00	-0.12	-0.16
6FFF	1.06	0.59	-0.18	-0.33
10MV	1.42	1.32	-0.08	-0.02
10FFF	1.28	1.02	-0.09	-0.22
15MV	1.39	1.32	-0.07	0.0

Table 2. Gamma pass rates for SRS plans with IC measured transmission and DLG.

Plan	Energy (MV)	Portal Dosimetry Gamma Pass Rates							
		Field 1		Field 2		Field 3		Field 4	
		3%/1mm	1%/1mm	3%/1mm	1%/1mm	3%/1mm	1%/1mm	3%/1mm	1%/1mm
SRS: Single Target	6F	77.2%	61.0%	89.5%	74.5%	76.3%	61.5%	83.0%	66.7%
	10F	99.3%	99.2%	99.9%	99.8%	99.1%	97.7%	100.0%	100.0%
	6X	96.4%	92.7%	98.0%	96.8%	93.9%	90.9%	96.4%	94.1%
	10X	94.6%	93.0%	94.1%	93.6%	92.3%	90.0%	95.3%	94.0%
	15X	95.0%	93.2%	94.4%	93.9%	92.4%	90.1%	95.4%	94.2%
SRS: Three Target	6F	99.4%	91.7%	97.8%	85.3%	85.5%	75.0%	95.4%	80.5%
	10F	99.6%	95.7%	99.8%	96.1%	94.1%	84.8%	99.4%	93.7%
	6X	99.7%	96.3%	99.3%	93.6%	99.0%	94.8%	98.6%	91.7%
	10X	99.2%	95.3%	97.7%	92.2%	97.8%	93.6%	98.5%	94.4%
	15X	95.3%	88.7%	94.3%	88.0%	93.4%	87.1%	95.2%	89.8%

Table 3. Gamma pass rates for SRS plans with EPID measured transmission and DLG.

Plan	Energy (MV)	Portal Dosimetry Gamma Pass Rates							
		Field 1		Field 2		Field 3		Field 4	
		3%/1mm	1%/1mm	3%/1mm	1%/1mm	3%/1mm	1%/1mm	3%/1mm	1%/1mm
SRS: Single Target	6F	99.9%	94.8%	100.0%	99.5%	97.9%	93.4%	98.1%	95.4%
	10F	99.8%	99.8%	100.0%	99.9%	99.6%	99.2%	100.0%	99.6%
	6X	96.0%	93.8%	96.6%	96.3%	92.9%	91.3%	95.6%	95.2%
	10X	94.8%	93.1%	94.6%	94.0%	92.4%	90.2%	95.4%	94.0%
	15X	95.2%	93.5%	95.0%	94.3%	92.6%	90.2%	95.5%	94.2%
SRS: Three Target	6F	100.0%	98.3%	100.0%	99.7%	99.3%	96.5%	98.8%	94.3%
	10F	99.9%	97.8%	100.0%	99.5%	99.7%	97.7%	99.8%	98.7%
	6X	99.2%	95.3%	97.8%	91.8%	98.6%	93.8%	97.9%	95.0%
	10X	99.3%	95.4%	97.5%	92.1%	97.9%	93.4%	98.5%	95.1%
	15X	95.6%	89.4%	94.6%	88.4%	93.9%	87.6%	95.5%	90.5%

Table 4. Gamma pass rates comparison for TG119 plans.

Plan	Energy (MV)	With measured transmission and DLG using IC				With measured transmission and DLG using EPID			
		2%/2mm		1%/1mm		2%/2mm		1%/1mm	
		Arc 1	Arc 2	Arc 1	Arc 2	Arc 1	Arc 2	Arc 1	Arc 2
Prostate	6X	93.8%	94.1%	76.6%	79.4%	91.4%	91.8%	71.2%	74.7%
	6F	99.3%	99.5%	95.5%	95.9%	99.5%	99.5%	95.1%	96.5%
	10X	91.2%	91.9%	66.3%	70.8%	91.1%	91.9%	66.1%	70.6%
	10F	99.8%	99.8%	96.6%	97.7%	99.5%	99.8%	94.6%	97.1%
	15X	81.3%	82.4%	57.8%	59.7%	81.6%	82.8%	58.4%	60.0%
HN	6X	99.9%	99.9%	97.4%	97.8%	100.0%	99.8%	94.3%	94.3%
	6F	99.4%	99.2%	89.8%	89.2%	99.9%	99.9%	97.7%	98.5%
	10X	99.8%	99.5%	89.3%	90.3%	99.7%	99.5%	87.9%	88.8%
	10F	99.9%	99.7%	97.2%	96.5%	99.9%	99.9%	97.9%	97.1%
	15X	94.5%	93.1%	67.5%	72.1%	95.0%	93.3%	67.2%	72.0%
C-shape	6X	99.2%	99.6%	95.1%	97.1%	98.9%	99.5%	93.6%	95.5%
	6F	99.6%	99.1%	92.5%	88.4%	100.0%	99.9%	98.7%	98.4%
	10X	99.9%	99.7%	95.4%	97.1%	99.8%	99.7%	94.7%	96.8%
	10F	99.9%	99.8%	97.2%	96.8%	100.0%	99.9%	98.6%	98.0%
	15X	96.90%	97.7%	85.2%	87.8%	97.0%	97.7%	85.2%	87.7%

DISCUSSION

Comparison of the measured MLC leaf transmission and dosimetric leaf gap (DLG) between the ionization chamber (IC) and EPID demonstrated the largest differences for the flattening filter-free (FFF) photon beams. For example, the measured MLC transmission for the 6FFF beam decreased from 1.06% with the IC to 0.59% with the EPID, representing a reduction of more than 44%. This difference can be explained by the energy-dependent response of the amorphous silicon EPID. The open beam contains a relatively larger proportion of low-energy photons, to which the EPID exhibits increased sensitivity. In contrast, transmission through the MLC preferentially attenuates low-energy photons, resulting in a harder photon spectrum than that of the open beam. Consequently, the EPID response to MLC-transmitted radiation differs from its response to the open reference beam, leading to lower measured transmission values.
This energy-dependent detector response affects portal dosimetry because the treatment planning system (TPS) beam model is based on MLC transmission and DLG parameters. If conventional IC-measured transmission and DLG values are used without accounting for the EPID response, the calculated portal dose may not accurately represent the measured EPID image, resulting in reduced gamma passing rates. This effect is demonstrated by the comparisons presented in Tables 2–4, where the TPS commissioned with EPID-measured transmission and DLG values consistently produced improved portal dosimetry agreement for both SRS and TG-119 VMAT plans.

In clinical practice, separate detector-specific commissioning parameters may therefore be required for portal dosimetry. Because the EPID cannot distinguish between open-field and MLC-transmitted radiation during image acquisition, a separate calibration factor for MLC transmission cannot be directly applied during measurement. Instead, the TPS beam model used for portal dosimetry should incorporate EPID-specific MLC transmission and DLG values to compensate for the detector's energy-dependent response. In contrast, patient and phantom dose calculations should continue to use the IC-based commissioning parameters, which more accurately represent the absorbed dose in water and therefore provide the appropriate basis for treatment planning.

CONCLUSIONS

Differences were observed in the measured MLC leaf transmission and dosimetric leaf gap (DLG) values obtained with the ionization chamber (IC) and electronic portal imaging device (EPID). The EPID consistently measured lower MLC transmission and DLG values, reflecting its energy-dependent response to the hardened photon spectrum produced by MLC transmission through the leaf body and leaf ends.
Portal dosimetry results were influenced by the detector used to determine the MLC transmission and DLG values for treatment planning system (TPS) commissioning. When EPID-measured transmission and DLG values were incorporated into the TPS beam model for portal dose prediction, gamma passing rates improved substantially and consistently met clinical acceptance criteria, particularly for flattening filter-free (FFF) beams.
These findings demonstrate that detector-specific commissioning parameters are important for accurate EPID-based portal dosimetry. The TPS should therefore incorporate EPID-specific MLC transmission and DLG values, or an equivalent correction for the EPID's energy-dependent response, when predicting portal dose. In contrast, patient dose calculations should continue to use ionization chamber-based commissioning parameters to maintain accurate absorbed-dose calculations in medium.

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