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Original paper

Feasibility study of an electronic portal imaging based in vivo dose verification system for prostate stereotactic body radiotherapy

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ABSTRACT

Purpose: We evaluated the feasibility of electronic portal imaging based 3D in-vivo dosimetry for stereotactic body radiation therapy (SBRT) technique in prostate cancer.

Methods and materials: To investigate error detectability limitations of iViewDose™ v.1.0.1 (Elekta, Stockholm, Sweden) for prostate SBRT cases, ten prostate cancer patients were selected and in-vivo electronic portal imaging devices dosimetry was performed. Also possible error scenarios including dose calibration, setup, collimator, multi leaf collimator and patient anatomy related inaccuracies were created to investigate detectability of EPID. For this purpose, a SBRT treatment was planned on BrainLab pelvis phantom (BrainLab Medical Systems, Westchester, IL) and irradiated after proving setup with cone beam computer tomography. After that incorrect plans were irradiated and obtained results were compared with original in vivo measurements.

Results: Mean gamma analysis ($\gamma\% \leq 1$) passing rate of ten patients was found as 96.2%. Additionally, mean dose reference point difference between measurement and calculated in treatment planning system for clinical target volume, rectum, bladder, left and right femur heads were found as 1.4%, 8%, 20.8%, 2.3% and 4.5%, respectively. Phantom measurements showed that positional errors can be escape from detection. However, the incorrect treated plans including linac calibration, MLC positions and patient anatomy based errors could not have passed the in vivo dosimetry analysis. Conclusions: EPID-based 3D in vivo dosimetry software (iViewDose) provides an efficient safety check on the accuracy of dose delivery during prostate SBRT treatments. However, phantom results showed some limitation of the system.

1. Introduction

Stereotactic body radiation therapy (SBRT) is capable of delivering very large and precise dose of radiation, and has emerged as a primary treatment for low and intermediate risk prostate cancer [1,2]. Accurate imaging and tracking of the target regions allows clinicians to reduce treatment margins and maximally spare rectum, bladder, urethra and penile bulb [3]. However, very sharp dose gradients and the proximity of critical structures to prostate requires precise verification of treatment plans [4,5]. In this aspect, quality assurance (QA) procedures consist of point dose measurements, 2D or 3D dose examinations either prior to radiotherapy or during treatment process. QA procedures are generally carried out by the transfer of approved treatment plans to the phantom. Pre-treatment quality controls may detect several potential errors, as they are not appropriate to detect the dosimetric uncertainties that may occur during treatment, particularly due to the changes in patient's anatomy and positioning errors. Therefore, the quality of actual treatment remains unclear. These uncertainties can be eliminated by real-time in vivo dosimetry systems. However, such systems perform only point dose measurements.

Electronic portal imaging devices (EPID) are the most widely used dose verification systems [6–8]. EPID was originally designed for setup validation, they are also used to perform pre-treatment dose verification in quality control applications [9–12]. Recently, EPID based systems are used as in vivo dosimetry system, since they include the transit dose information [13–16].

Markus Wendling et al. from the Netherlands Cancer Institute (NKI)-Antoni van Leeuwenhoek Hospital introduced a back-projection algorithm for 3D EPID dosimetry of intensity modulated radiation therapy (IMRT) [17,18]. Their method has been used in NKI for IMRT verification since 2008. Then, Anton Mans et al. demonstrated the feasibility of back-projection portal dosimetric verification of volumetric arc therapy (VMAT) plans [19]. In terms of clinical applications, Ben J. Mijnheer reported the results of 15,076 plans [20]. They emphasized that a majority of the errors were due to anatomical changes, and those errors could not be detected by pretreatment verification.

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Elekta (Stockholm, Sweden) recently developed commercially available iViewDose™ (Elekta, Stockholm, Sweden) software as a solution for in-vivo EPID dosimetry in conjunction with the NKI. iViewDose software allows users to reconstruct delivered dose in 3D on planning CT. In our institution, iViewDosein vivo dosimetry checks is being performed for each fraction of treatments for VMAT, SBRT and IMRT plans. In this study, in vivo dosimetric results of 10 prostate SBRT patients were investigated, and a phantom study was additionally performed. Possible error scenarios were created to determine the factors affecting the pass rate of gamma results of prostate SBRT plans. In addition, the detectable limits of the aforementioned errors were investigated.

2. Materials and methods

2.1. In vivo measurements

Ten prostate cancer patients receiving 36.5 Gy in 5 fraction were enrolled in this study. All treatments were performed with VMAT using Elekta Versa HD™ (Elekta, Stockholm, Sweden) treatment machine. Patients received 6 MV FFF photon beams with 2 arcs, which were described from 190° to 170° in clockwise direction and other from 170° to 190° in counter clockwise direction. Raystation treatment planning system (TPS) was used to create plans with 700 MU/min dose rate. We used an EPID with amorphous silicon flat panel-type imager (Elekta iViewGT).

The treatment machine was daily calibrated to obtain 1 cGy dose at 1.5 cm depth in water equivalent solid phantoms with 1 MU. Setup verification was maintained for each fraction with cone beam computed tomography (CBCT) images. After the position of patient was verified by physician, radiotherapy was started and transit radiation dose information was simultaneously collected by iViewGt (Elekta,Stockholm, Sweden) in every fraction. The collected data was automatically exported to the iViewDose software.

iViewDose compares the EPID-reconstructed dose with the planned dose. The transit dose information during treatment is required to analyze the gamma results for VMAT plans.

3D gamma evaluation per fraction was used for analysis. γ_{mean}, $\gamma_{1\%}$ and $\gamma \leq 1\%$ (Gamma criterion: 3% global dose difference/3 mm distance to agreement, threshold 50%) values were examined to evaluate the treatment quality. The pass rate criteria were described as 0.7, 2.0 and 95%, respectively.

Dose reference point (DRP) values were used for the comparison of point dose measurement results. The software allows us to select a structure to define DRP, which is placed into the mass center of the delineated structure. For the selected structures, the algorithm of iViewDose software calculates the percentage dose difference between TPS and obtained dose from the EPID which is reconstructed on the treatment CT. The acceptance criterion was set at 3% for PTV. Other DRPs were also recorded.

2.2. Phantom measurements

The phantom measurements were carried out with BrainLab pelvis phantom (BrainLab Medical Systems, Westchester, IL) to examine the detection capability of IviewDose for possible errors. Different scenarios were created for this purpose including positional changes, dose, collimator angle or dose rate differences and weight loss of patient.

3D gamma analysis was performed to compare predicted and measured dose. Additionally, DVH parameters of simulated errors were computed in TPS, since the iViewDose software does not support DVH based analysis in current version. $D_{95\%}$, for bladder D_{3cc} and for rectum D_{1cc} parameters for PTV were used to investigate the impact of simulated errors on treatment.

CTV, PTV and critical structures including rectum, bladder, left and right femur heads were contoured on the phantom's CT images by an expert radiation oncologist. A treatment plan was created for the pelvis phantom using 6 MV FFF photon beams with 700 MU/min maximum dose rate and 2 arcs from 190 to 170 in direction clock wise and 170 to 190 in direction counter clock wise. This plan and measurement were considered as the original plan and the original measurement.

The pelvis phantom was deliberately placed to incorrect positions towards to anterior, superior and left directions for the ability of catching positional errors. The shifts were adjusted as 1, 2 and 5 cm for each direction. In this scenario, CBCT was acquired for the initial image registration. Then, treatment couch was shifted and adjusted towards to the given directions and values. The phantom irradiated incorrect position and transit dose information was collected, and gamma analyses results were obtained by iViewDose software.

Lineer accelerator setup calibration was set to cause a dose difference of 1%, 3% and 5% for the detectability of dose differences. After irradiation, γ-evaluation was performed, and the results were compared with the original results.

To simulate detectability of collimator angle inaccuracies, the pelvis phantom was irradiated with 0.5°, 2° and 5° angular deviations. γ-evaluation was performed with the original treatment plan.

The phantom was irradiated with 3 discrete maximum dose rate levels which are 100, 300 and 1400 MU/min to catch if there was an error due to the dose rate differences on dose distribution. Furthermore, it was checked whether the via iViewDose gamma results were affected by dose rate.

Patient weight change was simulated with bolus. Before irradiation, the pelvis phantom was covered with 1 cm thickness bolus. The measurements were also repeated for 2 cm thickness bolus. Gamma analyses were performed and compared with original plan.

The detectability of the MLC errors has been tested with incorrectly positioned MLC pairs. One of the MLC pairs in the middle of the field was kept closed. Then, the phantom was irradiated and results were evaluated.

3. Results

3.1. In vivo measurements

In general, the EPID reconstructed gamma evaluations and the planned dose distributions for ten prostate SBRT plans displayed excellent results for in vivo verification (Table 1). The mean passing rate was observed 96.2% (criteria: 3% global dose difference/3 mm distance to agreement, threshold 50%). The maximum calculated DRP's dose difference for PTV was 2.7%. The mean DRP differences for rectum, bladder, left and right femur heads were calculated as 8%, 20.8%, 2.3% and 4.5%, respectively (Table 2).

Table 1
Gamma evaluations results for prostate SBRT patients.

Patients	$^{\gamma}$ mean	$^{\gamma}$1%	$\%^{\gamma} \leq 1$	Dose at isocenter		
				Plan Reference(Gy)	EPID Mean(Gy)	ΔDRP (%)
1	0.4	1.3	95.0	7.4	7.6	2.7
2	0.4	0.8	99.7	7.3	7.3	0.3
3	0.5	1.3	93.6	7.4	7.4	0.3
4	0.5	1.7	95.5	7.4	7.5	1.3
5	0.4	1.1	97.9	7.3	7.6	3.6
6	0.5	1.6	92.7	7.4	7.6	2.2
7	0.4	1	99.0	7.4	7.3	1.2
8	0.3	0.8	99.9	7.5	7.6	0.8
9	0.3	0.7	100.0	7.3	7.4	0.5
10	0.4	1	98.7	7.4	7.3	0.6

Table 2
Reference, measured dose and percentage difference for critical structures.

	DRP Rectum			DRP Bladder			DRP Left Femur			DRP Right Femur		
	Plan	EPID		Plan	EPID		Plan	EPID		Plan	EPID	
Patients	Reference (Gy)	Mean (Gy)	ΔDRP (%)	Reference (Gy)	Mean (Gy)	ΔDRP (%)	Reference (Gy)	Mean (Gy)	ΔDRP (%)	Reference (Gy)	Mean (Gy)	ΔDRP (%)
1	4.3	4.6	6.8	0.1	0.1	19.2	0.9	0.9	7.7	1.4	1.5	3.3
2	1.5	1.8	22.8	0.3	0.4	33.9	1.5	1.4	3.2	1.3	1.3	4.3
3	2.5	2.8	10.3	3.5	3.6	5.5	1.8	1.9	4.6	1.1	1.2	8.8
4	3.6	4.0	9.1	2.2	2.6	18.4	2.3	2.3	0.2	2.2	2.2	1.1
5	2.9	3.0	3.8	0.4	0.5	27.3	2.3	2.4	0.9	1.7	1.9	6.3
6	3.4	3.1	8.4	1.1	1.6	35.6	2.6	2.6	0.4	2.4	2.3	1.2
7	6.3	6.1	2.8	0.2	0.2	11.5	2.0	2.0	0.6	2.0	2.0	0.6
8	1.3	1.4	8.1	2.4	2.8	15.5	2.7	2.6	0.6	2.6	2.7	2.2
9	4.2	4.4	2.7	0.2	0.3	28.3	2.3	2.3	3.2	1.5	1.7	8.7
10	3.0	3.1	4.9	2.0	2.3	13.0	2.8	2.7	1.8	2.5	2.7	8.3
Mean			8.0			20.8			2.3			4.5

Table 3
Gamma analysis results of the phantom measurements.

	Total Gama Results	Isocenter(%)	Isocenter(Gy)
Original Plan	98.3	1.8	7.7
5 cm Left	86.7	4.0	7.9
5 cm Anterior	67.7	7.5	8.1
5 cm Superior	31.8	10.3	8.4
1 cm Left	97.7	1.9	7.7
2 cm Left	96.8	2.2	7.7
1 cm Superior	94.5	3.2	7.8
2 cm Superior	86.1	4.4	7.9
1 cm Anterior	97.7	2.1	7.7
2 cm Anterior	97.4	2.7	7.8
Dose Rate 1400	98.0	1.9	7.7
Dose Rate 100	96.6	1.6	7.7
Dose Rate 300	98.0	1.9	7.7
0.5 Collimator	98.1	1.9	7.7
2 Collimator	98.3	1.9	7.7
5 Collimator	97.8	1.9	7.7
1% Dose Difference	97.5	3.0	7.8
2% Dose Difference	93.3	3.9	7.9
5% Dose Difference	71.2	7.0	8.1
1 cm Bolus	92.4	−1.3	7.5
2 cm Bolus	75.5	−4.1	7.3

3.2. Phantom measurements

The passing rate of gamma evaluation for original plan was calculated as 98.3% for the pelvis phantom. Dose differences at isocenter was measured to be 1.8%. Table 3 summarized gamma analysis results for all scenarios. Shifting the phantom 1 cm superiorly from original position was detected by EPID in vivo dosimetry system with a passing rate of 94.5%. However, 1 cm position change in either anterior or left direction could not be detected. Gamma evaluation results for this scenarios were 97.7% and 97.7%, respectively. A 2 cm position replacement was also detected for only superior direction with a passing rate of 86.1%. Gamma evaluation results for the displacements of anterior and left direction were 97.4% and 96.8%, respectively. A 5 cm displacement of the phantom was easily detected for all directions. Gamma evaluation values for superior, anterior or left directions were 31%, 67.7% and 86.7%, respectively.

Gamma evaluation results for different dose rates successfully passed the test, though passing rate scores decreased for 1000 MU/min. Changes in dose rates did not affect the validity of the results.

All results were acceptable for incorrect collimator angles. Nevertheless, the minimum passing rate was detected for 5° deviations.

The system was quite successful in detecting dose differences. A 1% dose change was passed the gamma evaluation, but the isocenter dose difference increased at the same rate. On the other hand, 2% and 5% dose differences were failed. In addition, the measured isocenter doses were 2.2% and 5.3% higher than the reference measurements.

iViewDose's performance was satisfactory during simulating the weight changes in patients. Covering the phantom with bolus was noticed by in vivo dosimetry system. Furthermore, the calculated isocenter doses decreased.

Gamma evaluation result was 67% for incorrectly positioned MLC pair. The calculated dose of isocenter decreased by 20% compared to the original plan. Dose differences were obtained in slices under closed MLC pair (Fig. 1). A sharp reduction in dose due to closed MLC pair was easily visible as demonstrated in Fig. 1.

Table 4 displays the dosimetric impact of simulated errors obtained from TPS. All simulated positional errors reduced PTV $D_{95\%}$ values to clinically unacceptable levels. PTV $D_{95\%}$ and rectum D_{1cc} values did not change for 0.5 collimator error scenario. However, it resulted in a 1% dose difference for bladder $D_{3cc.}$ The dose difference increased by increasing collimator angle error. Dose difference errors resulted in a change in the doses of PTV, bladder and rectum at the same rate.

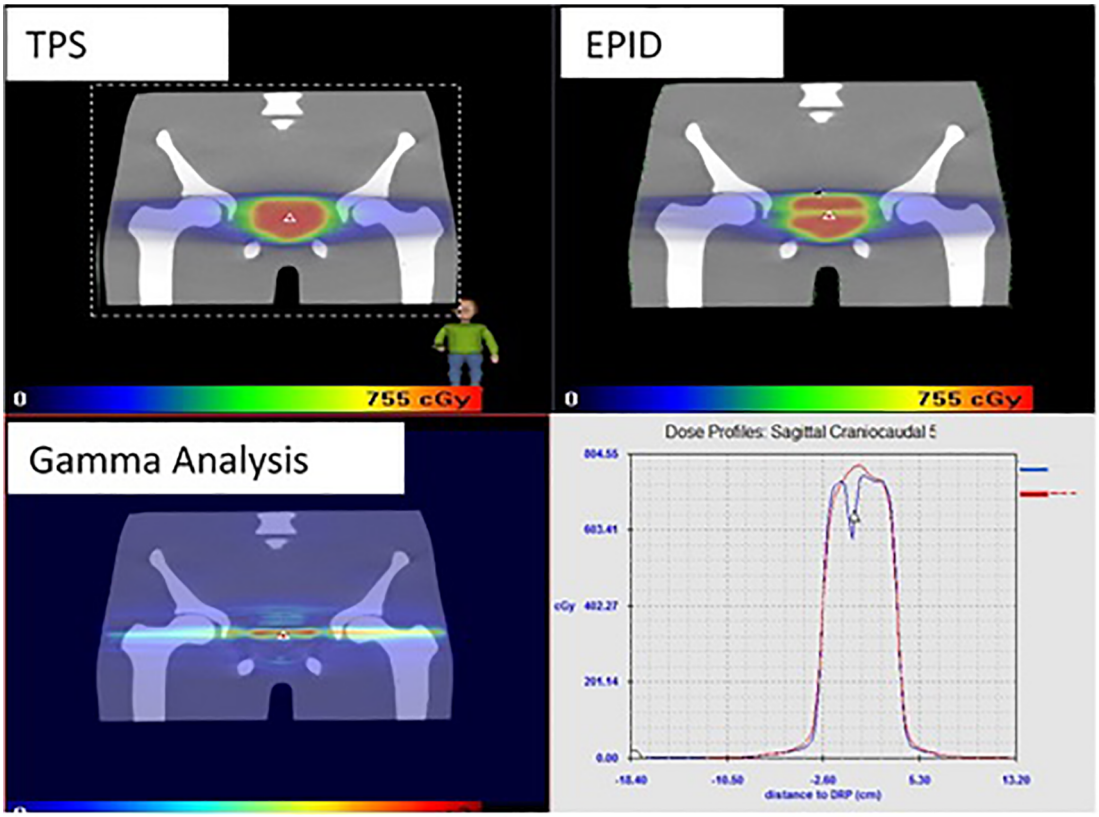

Fig. 1. Gamma evaluation for incorrectly positioned MLC pair.

Table 4
Percentage dose difference for PTV $D_{95\%}$, Bladder D_{5cc} and Rectum D_{1cc} according to the original treatment plan. Minus sign indicates the decreasing dose.

	ΔPTV $D_{95\%}$ (%)	ΔBladder D_{5cc} (%)	ΔRectum D_{1cc} (%)
1 cm Left	−19.5	−0.8	−5.6
2 cm Left	−46.7	−2.0	−16.9
5 cm Left	−74.9	−33.4	−45.1
1 cm Anterior	−29.9	2.5	−36.8
2 cm Anterior	−61.5	3.9	−65.6
5 cm Anterior	−84.6	8.4	−84.9
1 cm Superior	−34.3	5.6	−40.7
2 cm Superior	−87.9	6.9	−44.2
5 cm Superior	−98.8	7.8	−62.9
0.5 Collimator	−0.3	−0.8	0.0
2 Collimator	−6.2	−0.8	0.3
5 Collimator	−12.4	−0.8	0.0
1%dose difference	0.9	0.3	0.9
2%dose difference	2.1	1.4	2.1
5%dose difference	5	4.5	5.3
1 cm bolus	−5.6	0.0	0.3
2 cm bolus	−11.2	0.0	0.6

4. Discussion

To the best of our knowledge, this is the first study investigating the clinical performance of iViewDose in vivo EPID dosimetry system for prostate SBRT patients. In addition to our results obtained from the actual patients, the results of the phantom measurements provided us the detection of possible errors in various scenarios to investigate the feasibility of this system.

Our patient-specific in vivo dose measurement results are comparable with the other studies performing clinically transit dosimetry. Mijnheer et al. reported 1.28 ± 3.18% dose difference for 379 prostate patients [20]. Their warning rates were 29%, when 3% alert criterion was applied. Francois et al. ascertained 1.6 ± 2.4% mean dose differences at the isocenter for 20 prostate cancer patients treated with 3D conformal plans [21]. We observed a 1.4 ± 1% mean difference between reconstructed doses and planned doses at DRP for prostate SBRT patients. The acquisition of CBCT images and the provision of immobilization conditions prior to each fraction can be effective in monitoring these results in the current study.

It was observed that displacement of the phantom 5 cm in any direction can be detected. However, shifting the phantom 1 and 2 cm from original position was detected only for superior direction. Mans et al. previously published that one of the limitations of EPID in vivo dosimetry was the detection of patient shift in the beam direction for IMRT patients [22]. In addition to Mans et al., our phantom measurements indicate that lateral displacements up to 2 cm escaped from the detection. The directional dependence of the catching errors could be caused by the regular body shape of the phantom. Because, a part of beam for superior direction shifted to the air between the legs of phantom. On the other hand, there were no body irregularities in other directions which may influence the fluence of beam. Our findings are consistent with the results of other studies that mention the failure of EPID dosimetry in positioning errors [22–24]. To prevent this kind of errors, it is suggested that EPID transit dosimetry must be used in combination with IGRT procedures [24,25].Collimator angle errors for 0.5 to 5° escaped from detection. On the contrary, Mijnheer et al. reported that collimator rotation angle errors could be detected by EPID dosimetry [23]. In their study, collimator errors were created changing angles from 20° to 340° or vice versa. However, Puchades et al. reported that there was a noticeable loss of PTV dose coverage with a relative variability of up to 75% for collimator angle errors greater than ± 1° for high-risk prostate cases [26]. The main reason for the failure of catching error might be due to the small and spherical shape of prostate.

The gamma results passed the evaluation for all different dose rates, and the calculated isocenter doses were almost the same. However, the

gamma values showed that the passing rate scores varied with the dose rate. Our results were similar to Winkler et al. [27]. They reported that the doubling the dose rate increased the EPID sensitivity by 1.5% for the same type detector. That behavior was attributed to the dose per frame effect in literature.

Creating 1%, 2% and 5% dose differences by changing calibration factor of linac were detected by EPID in vivo dosimetry. The calculated differences in the isocenter doses were 1.2%, 2.1% and5.2%, respectively. Only 1% dose deviation passed the gamma analysis. Previously Mijnheer et al. investigated the detectability of 5% MU changes for different planning models including prostate cases [23]. They observed that delivering 5% less MU could be detected by EPID causing 7.6% dose difference at isocenter. But the difference was 1.6% for 5% more MU This result has been associated with large differences in the original plan. Also Bedford et al. investigated the detectability of dose differences by increasing monitor unit from 2% to 10% in 2% for prostate plans. They reported that it could be detected by EPID using both forward and back projection method [28]. Our results showed that any calibration error could be detected by EPID in vivo dosimetry system for prostate SBRT patients.

Thickness errors were caught with EPID dosimetry system for prostate SBRT patients. Covering the phantom with 1 cm bolus material changed the isocenter dose 3% relative to the original treatment plan. Our findings for 1 cm thickness were in agreement with the results of several studies in literature. Pair et al. showed that 1 cm thickness difference for pelvic region resulted in 3.9% change in mean target dose [29]. For isocenter dose, Mijheer et al. observed a 4.1% difference for prostate cases [23]. The addition of 2 cm bolus material showed a 6.5% change in isocenter dose. Furthermore, the expected dose reduction in the isocenter due to the increase in thickness was observed by the EPID dosimetry system. We also showed that EPID dosimetry could capture errors caused by MLC position for prostate SBRT plans. Recently, Minjheer et al. observed that EPID-based 3D transit dose verification can detect single and multiple leaf position errors for head and neck, prostate and lung cancer cases. They also mentioned that lung cases were much more sensitive than other cases to small changes due to the small size of target. In the case of prostate, their findings showed that a change of 10 mm in single leaf position or 5 mm in three leaves could be detected. Since the size of irradiated areas for SBRT patients are much smaller than the more advanced diseases, the shape and size of the target affect the results, those inceptions are thought as the threshold for MLC position error detectability.

TPS analysis has shown that simulated errors can lead to clinically unacceptable treatment plans. Particularly positional errors caused very large dose differences. Unfortunately, these errors could not have been detected by in vivo EPID dosimetry. Olaciregui-Ruiz et al. introduced that the alert threshold values and the magnitude of the error could be detected were site-specific for patient-related errors. Their results showed that error detectability to patient position shifts was worse for pelvic treatments because variations in patient position for pelvic treatments have little effect on transmission [25].

Although the gamma index analysis is widely adopted in the clinical setting, many studies questioned whether it is capable of catching planning or machine errors [30–33]. The response and limitations of the gamma index analysis depend on measurement devices, algorithm, and pass rate criterion. Additionally, there are several studies mentioning that gamma passing rates correlate weakly with DVH parameters [34,35]. Alternative to γ criterions like γ mean, γ 1% and DVH based analysis were introduced to overcome these limitations [36,37]. The software used in our study does not support the DVH based analysis but it allows γ mean, γ 1%, γ ≤ 1% and point dose measurements.

5. Conclusion

To the authors' knowledge this is the first attempt in testing performance of commercially available software iViewDose for 3D in vivo dose verification of prostate SBRT cases. MLC, patient anatomy and dose calibration errors can be caught by iViewDose in vivo dosimetry system. On the other hand, we demonstrated that patient related positional errors and collimator deviations may escape from detection for prostate SBRT cases. Therefore, it is recommended to ensure that the patient setup is done correctly before performing in vivo dosimetry with EPID.

Declaration of Competing Interest

The authors have no conflicts of interest to disclose.

References

[1] Zelefsky MJ, Kollmeier M, McBride S, Varghese M, Mychalczak B, Gewanter R, et al. 5-Year outcomes of a phase I dose escalation study using stereotactic body radiosurgery for patients with low and intermediate risk prostate cancer. Int. J. Radiat. Oncol. Biol. Phys. 2019.

[2] King CR, Brooks JD, Gill H, Presti Jr. JC. Long-term outcomes from a prospective trial of stereotactic body radiotherapy for low-risk prostate cancer. Int. J. Radiat. Oncol. Biol. Phys. 2012;82:877–82.

[3] Mancosu P, Clemente S, Landoni V, Ruggieri R, Alongi F, Scorsetti M, et al. SBRT for prostate cancer: challenges and features from a physicist prospective. Phys. Med. 2016;32:479–84.

[4] Ezzell GA, Galvin JM, Low D, Palta JR, Rosen I, Sharpe MB, et al. Guidance document on delivery, treatment planning, and clinical implementation of IMRT: report of the IMRT subcommittee of the AAPM radiation therapy committee. Med. Phys. 2003;30:2089–115.

[5] Schreibmann E, Dhabaan A, Elder E, Fox T. Patient-specific quality assurance method for VMAT treatment delivery. Med. Phys. 2009;36:4530–5.

[6] Grządziel A, Smolińska B, Rutkowski R, Ślosarek K. EPID dosimetry – configuration and pre-treatment IMRT verification. Rep. Pract. Oncol. Radiother. 2007;12:307–12.

[7] Mousli M, Cummins D. EPID dosimetry for IMRT and VMAT PSQA. Phys. Med.: Euro. J. Med. Phys. 2018;52:173.

[8] Han B, Ding A, Lu M, Xing L. Pixel response-based EPID dosimetry for patient specific QA. J. Appl. Clin. Med. Phys. 2017;18:9–17.

[9] Bailey DW, Kumaraswamy L, Bakhtiari M, Malhotra HK, Podgorsak MB. EPID dosimetry for pretreatment quality assurance with two commercial systems. J. Appl. Clin. Med. Phys. 2012;13:3736.

[10] Woodruff HC, Fuangrod T, Rowshanfarzad P, McCurdy BM, Greer PB. Gantry-angle resolved VMAT pretreatment verification using EPID image prediction. Med. Phys. 2013;40:081715.

[11] Gustafsson H, Vial P, Kuncic Z, Baldock C, Denham JW, Greer PB. Direct dose to water dosimetry for pretreatment IMRT verification using a modified EPID. Med. Phys. 2011;38:6257–64.

[12] McCurdy BMC, McCowan PM. In vivo dosimetry for lung radiotherapy including SBRT. Phys. Med. 2017;44:123–30.

[13] Cilla S, Ianiro A, Craus M, Viola P, Deodato F, Macchia G, et al. Epid-based in vivo dose verification for lung stereotactic treatments delivered with multiple breath-hold segmented volumetric modulated arc therapy. J. Appl. Clin. Med. Phys. 2019;20:37–44.

[14] Nailon WH, Welsh D, McDonald K, Burns D, Forsyth J, Cooke G, et al. EPID-based in vivo dosimetry using Dosimetry Check: overview and clinical experience in a 5-yr study including breast, lung, prostate, and head and neck cancer patients. J. Appl. Clin. Med. Phys. 2019;20:6–16.

[15] Najem MA, Tedder M, King D, Bernstein D, Trouncer R, Meehan C, et al. In-vivo EPID dosimetry for IMRT and VMAT based on through-air predicted portal dose algorithm. Phys. Med. 2018;52:143–53.

[16] Consorti R, Fidanzio A, Brainovich V, Mangiacotti F, De Spirito M, Mirri MA, et al. EPID-based in vivo dosimetry for stereotactic body radiotherapy of non-small cell lung tumors: initial clinical experience. Phys. Med. 2017;42:157–61.

[17] Wendling M, Zijp LJ, McDermott LN, Smit EJ, Sonke JJ, Mijnheer BJ, et al. A fast algorithm for gamma evaluation in 3D. Med. Phys. 2007;34:1647–54.

[18] Wendling M, McDermott LN, Mans A, Sonke JJ, van Herk M, Mijnheer BJ. A simple backprojection algorithm for 3D in vivo EPID dosimetry of IMRT treatments. Med. Phys. 2009;36:3310–21.

[19] Mans A, Remeijer P, Olaciregui-Ruiz I, Wendling M, Sonke JJ, Mijnheer B, et al. 3D Dosimetric verification of volumetric-modulated arc therapy by portal dosimetry. Radiother. Oncol. 2010;94:181–7.

[20] Mijnheer BJ, Gonzalez P, Olaciregui-Ruiz I, Rozendaal RA, van Herk M, Mans A. Overview of 3-year experience with large-scale electronic portal imaging device-based 3-dimensional transit dosimetry. Pract. Radiat. Oncol. 2015;5:e679–87.

[21] Celi S, Costa E, Wessels C, Mazal A, Fourquet A, Francois P. EPID based in vivo dosimetry system: clinical experience and results. J. Appl. Clin. Med. Phys. 2016;17:262–76.

[22] Mans A, Wendling M, McDermott LN, Sonke JJ, Tielenburg R, Vijlbrief R, et al. Catching errors with in vivo EPID dosimetry. Med. Phys. 2010;37:2638–44.

[23] Mijnheer B, Jomehzadeh A, González P, Olaciregui-Ruiz I, Rozendaal R, Shokrani P, et al. Error detection during VMAT delivery using EPID-based 3D transit dosimetry. Phys. Med.: Euro. J. Med. Phys.. 2018;54:137–45.

[24] Esposito M, Bruschi A, Bastiani P, Ghirelli A, Pini S, Russo S, et al. Characterization of EPID software for VMAT transit dosimetry. Australas. Phys. Eng. Sci. Med. 2018;41:1021–7.
[25] Olaciregui-Ruiz I, Rozendaal R, Mijnheer B, Mans A. Site-specific alert criteria to detect patient-related errors with 3D EPID transit dosimetry. Med. Phys. 2019;46:45–55.
[26] Puchades V, Serna-Berná A, Mata-Colodro F, Ramos-Amores D, Alcaraz-Baños M. The importance of collimator angle error in volumetric-modulated arc therapy. J. Radiother. Pract. 2015;14:323–30.
[27] Winkler P, Hefner A, Georg D. Dose-response characteristics of an amorphous silicon EPID. Med. Phys. 2005;32:3095–105.
[28] Bedford JL, Hanson IM, Hansen VN. Comparison of forward- and back-projection in vivo EPID dosimetry for VMAT treatment of the prostate. Phys. Med. Biol. 2018;63:025008.
[29] Pair ML, Du W, Rojas HD, Kanke JE, McGuire SE, Lee AK, et al. Dosimetric effects of weight loss or gain during volumetric modulated arc therapy and intensity-modulated radiation therapy for prostate cancer. Med. Dosim. 2013;38:251–4.
[30] Nelms BE, Chan MF, Jarry G, Lemire M, Lowden J, Hampton C, et al. Evaluating IMRT and VMAT dose accuracy: practical examples of failure to detect systematic errors when applying a commonly used metric and action levels. Med. Phys. 2013;40:111722.
[31] Liang B, Liu B, Zhou F. Yin F-f, Wu Q. Comparisons of volumetric modulated arc therapy (VMAT) quality assurance (QA) systems: sensitivity analysis to machine errors. Radiat. Oncol. 2016;11:146.
[32] Zhen H, Nelms BE, Tomé WA. Moving from gamma passing rates to patient DVH-based QA metrics in pretreatment dose QA. Med. Phys. 2011;38:5477–89.
[33] Hussein M, Rowshanfarzad P, Ebert MA, Nisbet A, Clark CH. A comparison of the gamma index analysis in various commercial IMRT/VMAT QA systems. Radiother. Oncol. 2013;109:370–6.
[34] Stasi M, Bresciani S, Miranti A, Maggio A, Sapino V, Gabriele P. Pretreatment patient-specific IMRT quality assurance: a correlation study between gamma index and patient clinical dose volume histogram. Med. Phys. 2012;39:7626–34.
[35] Nelms BE, Zhen H, Tomé WA. Per-beam, planar IMRT QA passing rates do not predict clinically relevant patient dose errors. Med. Phys. 2011;38:1037–44.
[36] Rozendaal RA, Mijnheer BJ, van Herk M, Mans A. In vivo portal dosimetry for head-and-neck VMAT and lung IMRT: linking γ-analysis with differences in dose–volume histograms of the PTV. Radiother. Oncol. 2014;112:396–401.
[37] Visser R, Wauben DJL, de Groot M, Steenbakkers RJHM, Bijl HP, Godart J, et al. Evaluation of DVH-based treatment plan verification in addition to gamma passing rates for head and neck IMRT. Radiother. Oncol. 2014;112:389–95.