Original Article

Electronic Portal Imaging Device-Based Three-Dimensional Volumetric Dosimetry for Intensity-modulated Radiotherapy Pretreatment Quality Assurance

Manikandan Arjunan, Sureka Chandra Sekaran, Biplab Sarkar[1], Saran Kumar Manavalan[2]

Department of Medical Physics, Bharathiar University, Coimbatore, Tamil Nadu, [1]Department of Radiation Oncology, Manipal Hospital, Delhi, [2]Department of Radiation Oncology, Nagarjuna Hospital, Vijayawada, Andhra Pradesh, India

Abstract

Aim: This study aimed at evaluating the efficacy of treatment planning system (TPS)-based heterogeneity correction for two- and three-dimensional (2D and 3D) electronic portal imaging device (EPID)-based pretreatment dose verification. An experiment was conducted on the EPID back-projection technique and intensity-modulated radiotherapy (IMRT). **Materials and Methods:** Treatment plans were delivered in EPID without a patient to obtain the fluence pattern (F_{EPID}). A heterogeneity correction plane (F_{het}) for an open beam of 30 cm × 30 cm was extracted from the TPS. The heterogeneity-corrected measured fluence is developed by matrix element multiplication ($F_{Resultant} = F_{EPID} \times F_{het}$). Further planes were summed to develop a 3D dose distribution and exported to the TPS. Dose verifications for 2D and 3D were carried out with the corresponding TPS values using 2D gamma analysis (γ) and dose volume histogram (DVH) comparison, respectively. Totally, 33 patients (17 head–neck and 16 thorax cases) were evaluated in this study. **Results:** The head–neck and thorax plans show a 3-mm-distance to agreement (DTA) 3% DD gamma passing of 96.3% ± 2.0% and 95.4% ± 1.8% points, respectively, between F_{TPS} and $F_{Resultant}$. The comparison of the uncorrected measured fluence (F_{EPID}) with F_{TPS} reveals a gamma passing of 82.2% ± 7.3% and 80.4% ± 8.6% for head–neck and thorax cases, respectively. A total of 87 out of the 102 head–neck and thorax beams exhibit a planner gamma passing of 97.6% ± 2.1%. In the 3D-DVH comparison of thorax and head–neck cases, D5% for planning target volume were −0.5% ± 2.2% and −2.1% ± 3.5%, respectively; D95% varies as 1.0% ± 2.7% and 1.4% ± 1.1% between TPS calculated and heterogeneity-corrected-EPID-based dose reconstruction. **Conclusion:** The novel TPS-based heterogeneity correction can improve the 2D and 3D EPID-based back projection technique. Structures with large heterogeneities can also be handled using the proposed technique.

Keywords: Electronic portal imaging device dosimetry, intensity-modulated radiotherapy quality assurance, three-dimensional dosimetry

Received on: 10-05-2019 **Review completed on: 22-07-2019** **Accepted on: 06-08-2019**

Introduction

Intensity-modulated radiotherapy (IMRT) permits the delivery of a radiation dose conformally to the tumor sparing of normal tissues. IMRT can result in steep dose gradients between the target volumes and the organs at risk (OAR). IMRT delivery consists of the delivery of differential monitor unit (MU) over the static or dynamic multileaf-collimator-developed segments with static gantry angles. Therefore, good quality control process is necessary for the overall treatment planning, patient-specific quality assurance (QA), patient setup, and beam delivery.[1]

QA can be performed either before or during therapy delivery. The pretreatment verification consists of the examination of a set of treatment parameters such as MLC position, beam energy, and the number of MUs to ensure effective treatment delivery. These parameters can be used to reconstruct the dose distribution within a phantom.[2]

Several other methodologies are available for examining the absolute dose at specific points; this is generally carried out with ionization chamber measurements or planner dose

Access this article online

Quick Response Code:

Website: www.jmp.org.in

DOI: 10.4103/jmp.JMP_42_19

Address for correspondence: Dr. Sureka Chandra Sekaran, Department of Medical Physics, Bharathiar University, Coimbatore - 641 046, Tamil Nadu, India.
E-mail: surekasekaran@buc.edu.in

How to cite this article: Arjunan M, Sekaran SC, Sarkar B, Manavalan SK. Electronic portal imaging device-based three-dimensional volumetric dosimetry for intensity-modulated radiotherapy pretreatment quality assurance. J Med Phys 2019;44:176-84.

verification using film, ion chamber, or diode array.[3-6] These patient-specific QA methodologies are time-consuming and occasionally yield limited information. Approximately 1 h is required for ion chamber measurement when it is performed for each patient.[6] The most convenient method of patient-specific treatment plan verification is by using the portal imaging device (PID). Originally described by Greer and Popescu, electronic PID (EPID) is a reliable dose verification system when corrected for systematic shifts and tilts.[7-9] The two available methods for EPID dosimetry are suitable for pretreatment verification as well as *in vivo*/transit dosimetry. The first method is the forward approach, where the measured dose in the portal imager plane is compared to the dose or photon fluence predicted by the treatment planning system (TPS).[1,10-16] The second method is based on the back-projection approach, where the measured dose fluence at the EPID level in the presence (transit dosimetry) or absence of a patient (free air or phantom measurement) is back projected and reconstructed in the patient or in the phantom.[2,17-20]

The back-projection approach was efficiently used by several investigators including groups from the Netherlands Cancer Institute (AVL NKI), who successfully conducted a three-dimensional (3D) dose reconstruction as well as complete automated patient-specific EPID QA using a back-projection algorithm.[2,17,18,20-22]

However, in all their reports, their technique fails to detect large heterogeneities such as the lung and esophagus.[21,23,24] In certain cases, the investigators re-calculate the patient treatment plan in water by overriding the heterogeneity and verifying in EPID or omit the heterogeneity while reconstructing the 3D dose from the EPID-measured fluence.[19,21]

The failure to detect the heterogeneity is attributed to two factors. First, being a homogenous phantom, the EPID fails to comprehend the true human anatomy together with its heterogeneities; the second is the incompatibility of the dose calculation algorithm between the planning system (TPS) and EPID 3D dose reconstruction. The planning system dose calculation algorithm has evolved significantly from a pencil beam to the complete Monte Carlo system over the years; however, dose calculation algorithms embedded with portal dosimetry that are compatible with TPS have not been developed. Therefore, the back-projection algorithm is incapable of fulfilling the desired accuracy in the heterogeneous site(s). In their earlier report, the AVL-NKI group stated that a back-projection algorithm should verify the treatment planning independently and that its accuracy need not be as high as that of the TPS.[17] On the contrary, investigators have stated at different instances that a highly effective matching between TPS planned and measured dose reconstruction occurs if the same dose calculation algorithm is used for planning and QA. Nelms *et al*. attempted to utilize the same dose calculation algorithm for the QA approach; they succeeded in providing the pretreatment 3D dose to a patient using a dose perturbation concept.[25]

Present QA standards demand a comparison between planned and delivered doses in terms of dose-volume histogram (DVH). This requires 3D dose reconstruction from the delivered fluence in the presence (transit dosimetry) or absence (pretreatment QA) of the patient. There are several methods available for 3D dose reconstruction, which include EPID-based technique such as pretreatment, transit dosimetry, back projection, forward projection, diode or ion chamber array-based measurements and Monte Carlo simulation techniques.[1,12,15-19,25-30]

Nevertheless, neither the portal dosimetry nor the 3D dose reconstruction has attained the zenith, and there is scope for significant development in both the techniques, particularly in EPID dosimetry. Among all the EPID-based dosimetry approaches, transit dosimetry is an *in vivo* approach and the most effective method of QA. However, users are more likely to adopt the pretreatment QA as it reveals any problem associated with the treatment plans before actual delivery; moreover, it is occasionally specified as a legal requirement in a few countries.

In this study, we present a novel EPID-based 3D dose reconstruction technique using back-projection technique for pretreatment QA of IMRT delivery. It uses the same planning system for patient dose calculation as well as heterogeneity-corrected 3D dose reconstruction from the EPID-measured fluence. This aids the overcoming of the dose calculation algorithm incompatibility between the TPS and EPID-generated 3D dose. Furthermore, a DVH comparison and two-dimensional (2D) gamma analysis were carried out between the EPID reconstructed and TPS calculated dose.

Materials and Methods

Characteristic of amorphous silicon -based electronic portal imaging device

Portal images were acquired in an amorphous silicon (aSi)-1000 aSi EPID (Varian Medical Systems, Palo Alto, CA) associated with a Varian True Beam linear accelerator (Varian Medical Systems, Palo Alto, CA) equipped with 60 pair dynamic multileaf collimator (MLC). The EPID system consists of an image detection unit containing an imager panel and its associated electronics. The image is of dimensions 30 cm × 40 cm and pixel resolution 768 × 1024, yielding a pixel dimension of approximately 400 μm^2. Each pixel has a light-sensitive photodiode and a thin film transistor to enable the electronic readout. A digital to analog converter is used for converting the accumulated charge in the photodiode to an electronic signal. As specified by the manufacturer, an 8-mm water equivalent thickness is formed in front of the photodiode by a 1-mm copper plate and a layer of gadolinium oxysulfide used as the scintillating material. The image acquisition and processing are managed by Image Acquisition System 3 software (Varian Medical Systems, Palo Alto, CA). During the beam delivery, continuous acquisition of frames was

achieved. The accumulated 64 frame information were transferred to the control unit, resulting in an interruption in the image acquisition process. Nevertheless, the charge accumulation in the photodiode is not interrupted during the frame transfer, thus enabling an accurate acquisition of the final image. On completion of the beam delivery, a final grayscale image was formed by an averaging of the acquired frames. For the most simplistic approach, no additional build-up was used in our experiment. The manufacturer specified EPID pixel sensitivity consistency examination was performed before each measurement session.[31] EPID panel was calibrated to 1 CU = 1 cGy at isocenter plane at 600 MU/min, which is the dose rate used for IMRT.

However, the calibration was only for verifying the consistency; furthermore, only grayscale EPID images (relative measurement) are used for this study. All the IMRT plans were developed in the Varian's Eclipse (version 13.6) TPS.

Theory of dose reconstruction

Dose reconstruction was done on the basis of the open image. An energy fluence passing through a homogeneous medium shows a uniform decay. The correlation between initial and final fluence pattern is attributed to a uniform transmission factor. If (i, j) is the pixel matrix at the imager level then primary transmission through a uniform density phantom can be presented as

$$K_{iJ}^{Primary} = \exp\left(-\mu_{AT} \times t_{ij}\right) \quad (1)$$

where $K_{iJ}^{Primary}$ is the primary transmission, t_{ij} physical depth of (i, j) cell in phantom or patient and μ_{AT} is the attenuation coefficient at the said depth. Primary transmission will be further modified by a correction factor due to the scattering contribution N_S (i, j).

This total corrected fluence can be calculated as

$$I(i,j) = I_0(i,j) \times K_{iJ}^{Primary} \times N_S(i,j) = I_0 \times PDD\left(k_{ij}\right) \times OAR\left(k_{ij}\right) \quad (2)$$

where I (i, j) transmitted fluence for (i, j) cell, I_0 (i, j) incident fluence for (i, j) cell, PDD k_{ij} is the depth dose at physical depth of t for (i, j) cell, OAR (k_{ij}) is the off axis ratio for the cell (i, j) obtained from the profile curve. To obtain the planer fluence, each cell's transmitted fluence is integrated over the planar surface.

$$F_s = \iint_{x=-\frac{X_0}{2}y=-\frac{y_0}{2}}^{x=+\frac{X_0}{2}y=+\frac{y_0}{2}} I_0 \delta x \delta y \times K_{iJ}^{Primary} \times Ns(\delta x_i \delta y_i) \partial x \partial y \quad (3a)$$

where field size is defined as $x_0 \times y_0$ and origin is considered at the middle of the field. In the case of discreet acquisition, integration is changed to the summation.

$$F_s = \sum_{x=-\frac{X_0}{2}y=-\frac{y_0}{2}}^{x=+\frac{X_0}{2}y=+\frac{y_0}{2}} I_0(i,j) \times K_{iJ}^{Primary} \times N_s(I,j) \quad (3b)$$

For all practical purpose and order of magnitude used in radiotherapy (1 mm), an EPID with 400 μm resolution can be considered as a continuous medium; hence, equation (3a) can be used. F_s were obtained in 768 × 1024 matrix form, which represents a heterogeneity corrected planar fluence obtained from the portal imager. Each heterogeneity corrected planar fluence (F_s) was further exported to software platform Wolfram Mathematica V10.0 (Champaign, IL). Planes were interpolated and resampled at 2.5 mm bin; further a matrix summation was carried out to reconstruct the 3D dose and exported to the planning system.

Any commercially available TPS including Eclipse (excluding Monte Carlo TPS like CMS Monaco) uses a kernel-based algorithm. These kernels were derived from the user measured data of depth dose, profile, and output. In our measurement, we used the same data for the EPID dose reconstruction.

Pretreatment verification: Three-dimensional dose reconstruction and verification

The collection of heterogeneity-corrected dose fluence is a two-step procedure; the workflow is described in Figure 1. First, to obtain the contribution owing to the primary transmission and total scattering in the patient isocentric plane, an open field image of dimensions 30 cm × 30 cm was obtained from the TPS (F_{het}). This isocentric planar fluence contains the heterogeneity correction information in terms of scattering and attenuation. In the second step, the beam is delivered to the EPID in the absence of a scattering medium other than the EPID inherent buildup (F_{EPID}). F_{het} was normalized to deliver MU to obtain its relative grayscale image. Furthermore, both the fluence patterns were converted to a 256 × 256 matrix form and multiplied to obtain the resultant heterogeneity-corrected fluence pattern from the TPS ($F_{Resultant} = F_{EPID} \times F_{het}$). $F_{Resultant}$ is equal to the F_s in equation (3b). The EPID measurement yields only one 2D merged plane. The $F_{Resultant}$ for different planes separated by 1 cm was developed by calculating the F_{het} (extracted from TPS) and beam divergence for the particular plane throughout the anterior-posterior dimension of the patient, in OmniPro IMRT software (IBA Dosimetry, Schwarzenbruck,Germany). The corresponding planes from TPS (F_{TPS}) were also extracted for gamma analysis. The planes were enumerated from the beam entry point at the patient surface to the beam exit point. Furthermore, a 3D dose was reconstructed using each heterogeneity corrected planar fluence (F_s or $F_{Resultant}$) (as described in theory of dose reconstruction section) and exported to the Eclipse planning system for DVH comparison with the TPS calculated patient planned dose.

Measurement: Two-dimensional gamma analysis and three-dimensional dose-volume histogram analysis

Totally, 33 patients (17 head–neck and 16 thorax patients) were measured and verified for 2D gamma and 3D DVH analysis in this experiment. Twenty-eight planes for the thorax cases and 19 planes for the head–neck cases were reconstructed; these are the most common planes available in the respective patients. Gamma analysis (3%–3-mm) between F_{TPS} and $F_{Resultant}$ (γ: F_{TPS}

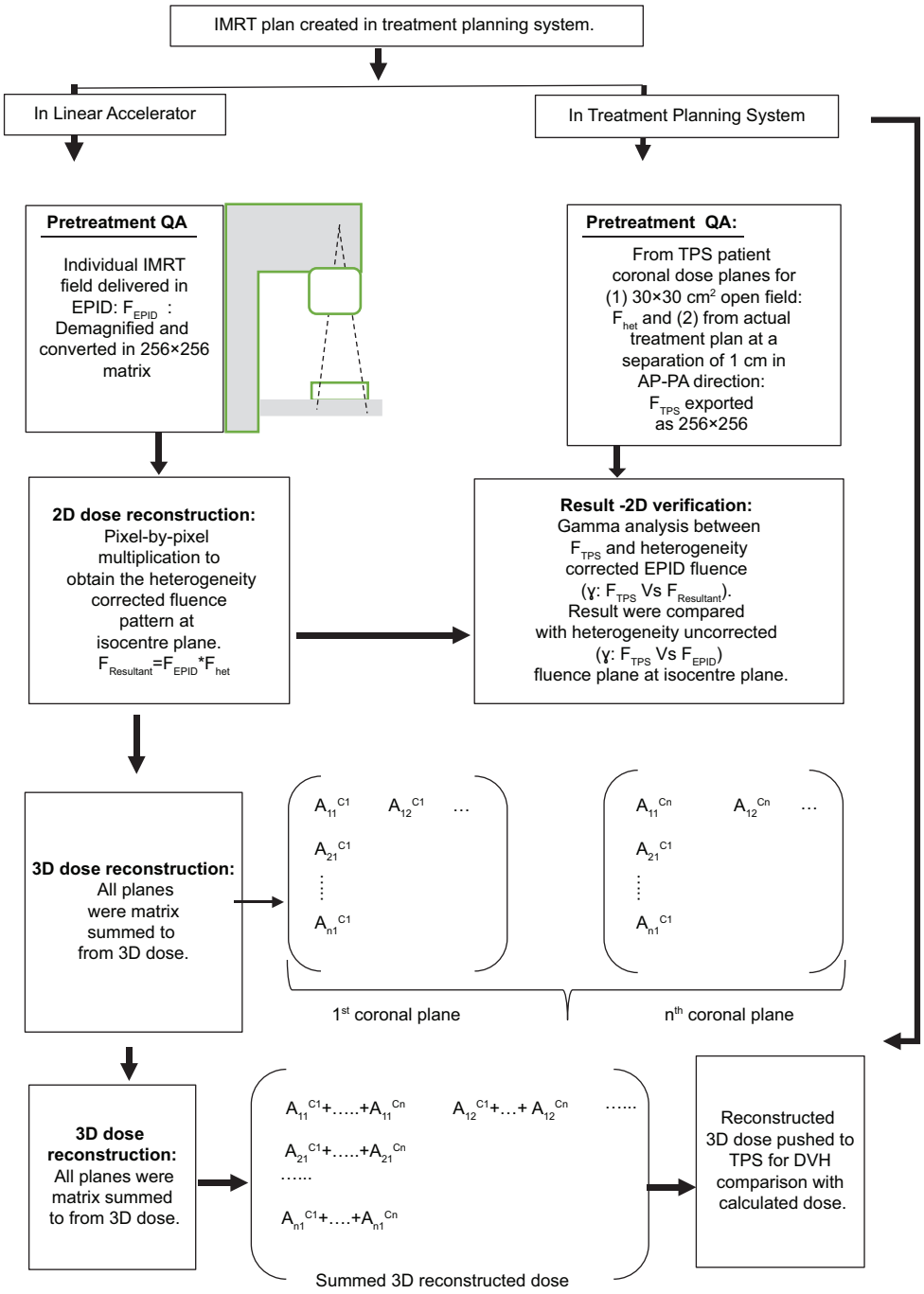

Figure 1: Workflow for electronic portal imaging device based two-dimensional and three-dimensional dose reconstruction and verification using heterogeneity correction

vs. $F_{Resultant}$) and F_{EPID} (γ: F_{TPS} vs. F_{EPID}) were carried out. The difference between (γ: F_{TPS} vs. $F_{Resultant}$) and (γ: F_{TPS} vs. F_{EPID}) establish the necessity of the heterogeneity correction. Figure 2 presents a typical gamma evaluation for a lung case with (γ: F_{TPS} vs. $F_{Resultant}$) and without (γ: F_{TPS} vs. F_{EPID}) heterogeneity correction.

For each patient, the TPS planned and 3D dose matrix reconstructed from the heterogeneity-corrected EPID fluence was compared with the actual treatment plan in the evaluation module of the Eclipse planning system (Varian Medical System, Palo Alto, CA). The 3D DVH analysis was carried out for all the cases for both the sites. Planning target volume (PTV) was evaluated for volume receiving 95% (D95%) and 5% (D5%) dose and spinal cord 0.1% (D0.1%) dose, which is representative of the maximum dose. Lung-gross tumor volume (GTV) (right and left lungs) was evaluated for the mean dose and volume receiving 5% (V5%), 10% (V10%), 20% (V20%), 30% (V30%), and 50% (V50%) doses. The heart was evaluated for V33% and V67% doses. For the head–neck cases, the parotid was

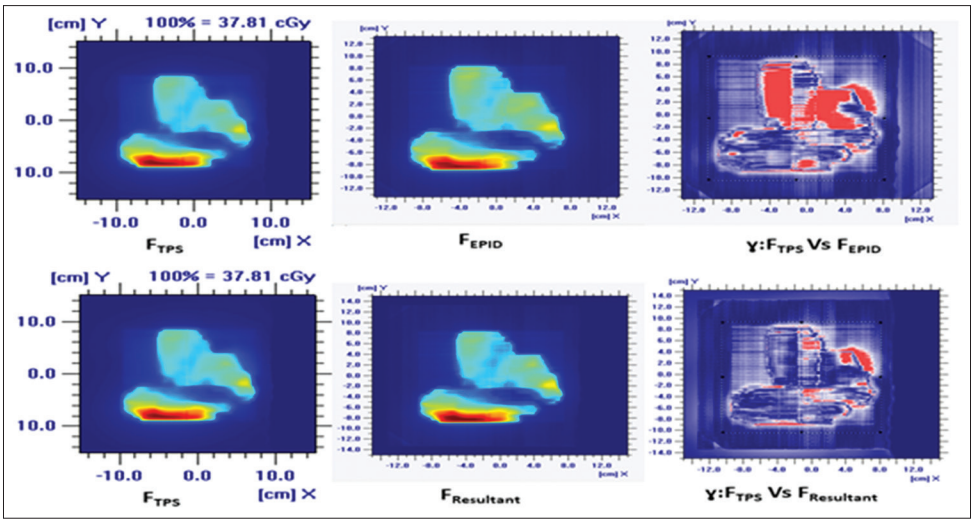

Figure 2: Dose distributions for a typical lung (thorax) patient for intensity-modulated radiotherapy at isocentric plane, F_{TPS}, F_{EPID}, $F_{Resultant}$ (=F_{EPID}*F_{het}) and their gamma matching for 3%-3mm gamma distribution. upper panel: $\gamma_{3mmDAT-3\%DD}$:: F_{TPS} Vs. F_{EPID} and lower panel: $\gamma_{3mmDAT-3\%DD}$:: F_{TPS} Vs. $F_{Resultant}$

evaluated for the mean dose, volume receiving 30 Gy (V30 Gy) and 20 Gy (V20 Gy) doses were administered; here, the mandible was for D0.1% (% volume receiving 0.1% dose), larynx was for the mean dose and swallowing structure was for D0.1% and the mean dose, according to our clinical protocol. Although the thorax cases have the lone PTV, head-and-neck cases are associated with one–three PTVs; PTV exhibited high risk, intermediate risk or low risk individually or in combination, as per the clinical staging. No remarkable variation in the dose-volume parameters was observed between the different PTVs. Therefore, they are presented in combination without characterizing their dose levels.

Patient distribution and radiotherapy treatment planning

All the thorax patients exhibit a solitary PTV; they are distributed over six patients having left lung tumor, six having right lung tumor and four having middle-lower esophagus tumor. For the head–neck cases, they are distributed over three primary oropharynx cases, three buccal mucosa cases, four larynx tumor cases, four tongue cases, and three base-of-tongue cases. All cases were planned by seven coplanar beams using a dynamic MLC IMRT technique. The used gantry angles are G-220°, G-250°, G-310°, G-0°, G-50°, G-110°, and G-140°. Collimator and couch angle were kept at 0°.

Results

Two-dimensional planar dose verification

All the plans in the head–neck and thorax cases yielded a 3-mm-DTA 3% DD gamma (γ: F_{TPS} vs. $F_{Resultant}$) passing of 96.3% ± 2.0% and 95.4% ± 1.8% points, respectively. Eighty-seven out of the 102 head–neck and thorax beams exhibit a planar gamma passing of 97.6% ± 2.1%; the remaining 15 fields exhibit a mean passing of 93.7% ± 2.1% for the 3%–3-mm criterion. All the thorax beams (78 in number) exhibit an overall passing of 95.8% ± 2.3%.

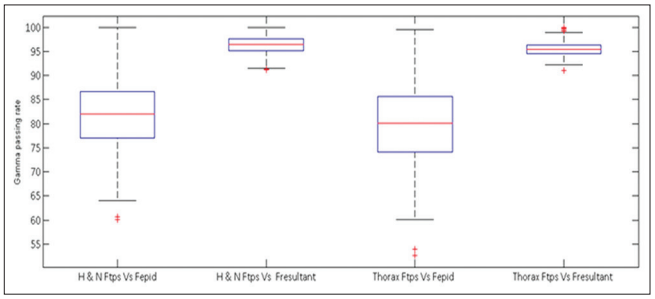

Figure 3: Average 3%–3mm gamma matching comparison γ: F_{TPS} vs. $F_{Resultant}$ and γ: F_{TPS} vs. F_{EPID} for head-neck and thorax cases

To verify the efficacy of heterogeneity correction on EPID-based dose verification, gamma matching between γ: F_{TPS} vs. $F_{Resultant}$ and γ: F_{TPS} vs. F_{EPID} are compared in Figure 3. The gamma analysis result for percentage points passing 3%–3-mm criteria between the EPID measured dose and TPS calculated dose without the heterogeneity correction for all the fields yields a mean gamma passing of 82.2% ± 7.3% and 80.4% ± 8.6% for the head–neck and thorax cases, respectively. In discussion, the efficacy of the TPS-aided heterogeneity correction is explained further.

Furthermore, the maximum and minimum gamma difference for the 3-mm DTA 3% DD gamma analysis result was evaluated using the following methodology. For each beam, the heterogeneity corrected gamma result (γ: F_{TPS} vs. $F_{Resultant}$) was compared with its heterogeneity uncorrected gamma result (γ: F_{TPS} vs. F_{EPID}). The minimum gamma difference for the head–neck and thorax cases were 5.1% and 7.5%, respectively; moreover, the maximum gamma differences for the same group were 26.3% and 29.4%, respectively.

Figure 2 presents a typical lung (thorax) patient for the IMRT dose distribution isocentric plane, F_{het}, EPID fluence and 3%–3-mm gamma distribution with and without the application of

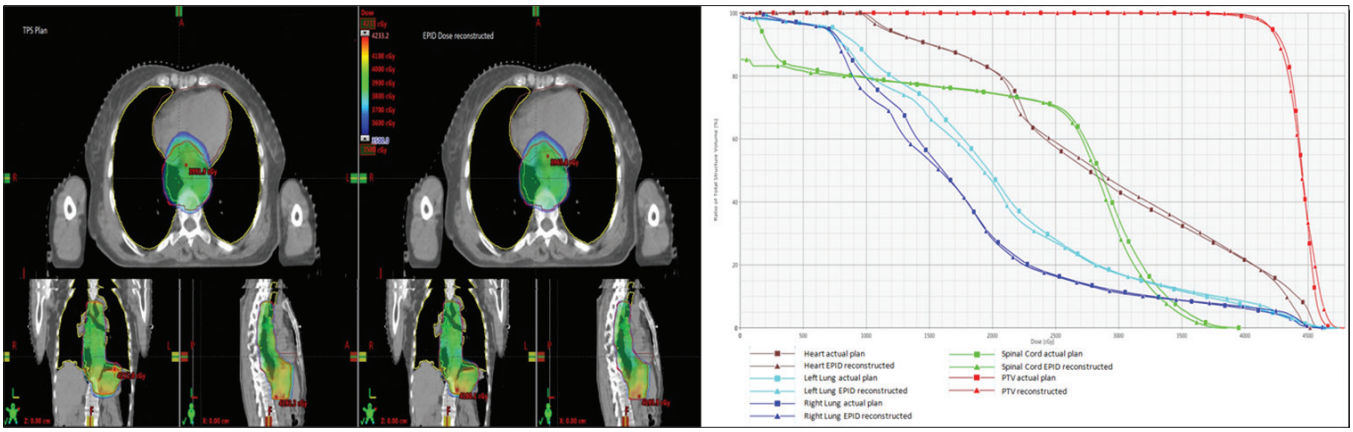

Figure 4: Visual and dose volume histogram comparison for the thorax cases

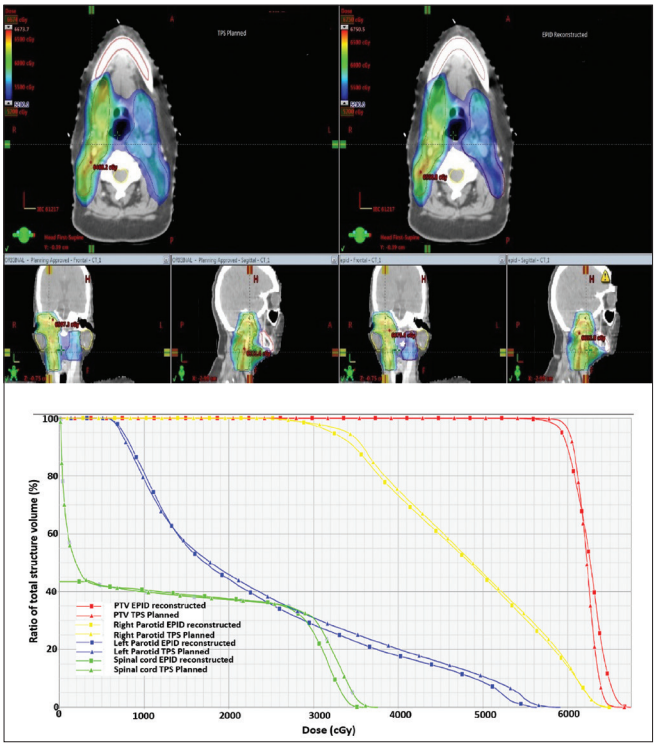

Figure 5: Visual and dose volume histogram comparison for head-neck cases

heterogeneity corrections. The significant decrease in gamma matching with and without the application of heterogeneity corrections is evident from upper panel where F_{TPS} vs. F_{EPID} and lower panel where F_{TPS} vs. $F_{Resultant}$ was compared for 3%-3mm gamma matching.

Three-dimensional dose verification

Figures 4 and 5 present the DVH comparison for the thorax and head–neck cases, respectively. Table 1 presents the relative (%) mean variation of the TPS measured and 3D reconstructed dose-volume parameters for the PTV and other OARs. The mean relative difference (± standard deviation) DVH parameters for the thorax (left column) and head–neck (right column) cases are presented in Table 1. D5% for PTV was −0.5% ± 2.2% and −2.1% ± 3.5% for the thorax and head–neck cases, respectively; here, D95% varies as 1.0% ± 2.7% and 1.4% ± 1.1% in the same sequence. The average difference in the lung-GTV dose for the thorax cases were 2.1% ± 3.8%; V5%, V10%, and V30% display differences ranging between 0.2% ± 3.1% and 3.7% ± 1.8%. The mean difference between the calculated and reconstructed dose was lower than 5% except for lungs-GTV at V50%, right lung at V30% and V50%, left lung at V20% and the V50% level in the thorax cases.

For the head–neck cases, the relative dose differences of mean, V30 Gy and V20 Gy for the left parotid were 3.3% ± 1.8%, 1.8% ± 2.1%, and 3.5% ± 1.1%, respectively; for the right parotid, the corresponding values were 1.0% ± 0.7%, 0.7% ± 1.8%, and 0.7% ± 0.8%, respectively. The relative differences of all the evaluated parameters for the head–neck cases yield a maximum and minimum variation for D0.1% of the spinal cord (4.2% ± 3.9%) and mandible (−0.2% ± 1.5%), respectively, and no organ dose variation exceeding ± 5%.

Discussion

A number of authors have described the EPID-based QA using different methods over the years.[32] These include measurement-based forward projection,[1,12-16,33,34] back projection[2,17,19,22,27-29] and Monte Carlo simulated in-air portal dose verification for Varian and Elekta EPID, respectively.[26,35] Forward projection is a technique, wherein the measured dose fluence from EPID is used as the input to either the TPS or in-house software, and 2D dose planes or 3D dose is reconstructed.[1,12-16,33,34]

The advantage of forward projection is the independent verification of the actual treatment plan. The plans created for portal dose verification need to be irradiated either in the air or in the presence of a scattering medium/phantom. This is a two-step process requiring the development of an independent plan and its verification. However, dose distribution recreated from the EPID measured fluence need to be verified for its accuracy. It is almost similar to having a two-planning process, which again requires a validation.

Table 1: Characteristics and dose-volume parameters applied for analysis of the different dose distributions of thorax and head–neck cases

Thorax			Head and neck		
Structure	**Parameter**	**Mean difference between calculated and dose reconstructed in % (±SD)**	**Structure**	**Parameter**	**Mean difference between calculated and dose reconstructed in % (±SD)**
PTV	$D_{5\%}$	−0.5±2.2	PTV	$D_{5\%}$	−2.1±3.5
	$D_{95\%}$	1.0±2.7		$D_{95\%}$	1.4±1.1
Spinal cord	$D_{0.1\%}$	2.7±4.2	Spinal cord	$D_{0.1\%}$	4.2±3.9
Lungs-GTV	Mean	2.1±3.8	Parotid left	Mean	3.3±1.8
	$V_{5\%}$	−1.0±5.2		V_{30Gy}	1.8±2.1
	$V_{10\%}$	0.2±3.1		V_{20Gy}	3.5±1.1
	$V_{20\%}$	6.0±2.1	Parotid right	Mean	1.0±0.7
	$V_{30\%}$	3.7±1.8		V_{30Gy}	0.7±1.8
	$V_{50\%}$	8.3±4.7		V_{20Gy}	0.7±0.8
Heart	$V_{67\%}$	−4.0±2.4	Oral cavity	Mean	2.0±1.0
	$V_{33\%}$	0.1±2.8	Mandible	$D_{0.1\%}$	−0.2±1.5
Right lung	Mean	1.7±3.2	Larynx	Mean	2.7±3.4
	$V_{5\%}$	0.8±5.7	Swallowing structure	$D_{0.1\%}$	3.1±3.7
	$V_{10\%}$	−0.1±1.9		Mean	2.1±3.1
	$V_{20\%}$	5.5±4.1			
	$V_{30\%}$	8.0±2.1			
	$V_{50\%}$	5.3±3.2			
Left lung	Mean	2.0±1.1			
	$V_{5\%}$	1.2±3.7			
	$V_{10\%}$	−0.1±2.9			
	$V_{20\%}$	5.5±1.7			
	$V_{30\%}$	4.0±0.8			
	$V_{50\%}$	7.9±1.2			

PTV: Planning target volume, GTV: Gross tumor volume, SD: Standard deviation

In back-projection methods,[2,17-22,27-29] the dose fluence obtained from EPID measurement is back-projected to the patient planes orthogonal to the beam axis. Furthermore, a 3D dose reconstruction was carried out using these back-projected planes. The advantage of back-projection over the forward projection is that it does not involve second dose calculation. Nevertheless, the back-projection algorithm described thus far is not efficient in handling the large heterogeneities in case of lung or thorax; this is because it uses a water-based correction kernel so that it cannot account for the true scattering conditions inside the patient.[19] The back-projection dose reconstruction is carried in a uniform density water phantom; this fails to yield an effective correlation with the actual patient dose calculation associated with the heterogeneities.

Our hybrid approach of introducing the TPS for the modification of the EPID measured dose can predict the large heterogeneity corrections very effectively. With regard to the rationality of incorporating the same TPS in portal dosimetry verification when it is important to verify the pretreatment QA independently, the rationale underlying the use of a TPS calculated heterogeneity correction in the EPID dose verification is explained below. The main disadvantage of the EPID dosimetry software that is commercially available at present or is available in-house is the incompatibility of the algorithm with the TPS. Planning system algorithms have evolved significantly over the past two decades. However, the EPID base dose verification software continues to use a pencil beam algorithm or does not consider the tissue heterogeneity.[10,19,36]

The refinement required for EPID dosimetry algorithms to improve on the dose calculation is at par with the planning system. In the present study, we incorporate a planning system to calculate the heterogeneity corrections; this further establishes that a TPS compatible result could be achievable with EPID dosimetry irrespective of the heterogeneity involved. As we have a lone TPS, it is necessary to consider the same TPS for patient dose calculation, EPID heterogeneity measurement and EPID-based dose reconstruction. However, it can be made completely independent if two independent, although mutually compatible (in terms of dose calculation algorithm), planning systems are available. Although we are the first group to use a treatment planning system for EPID-based QA, an earlier report has described its use in different QA methodologies.[25]

Few attempts have been undertaken for independently verifying the 3D doses using the EPID-based measurement[33] or using other detector systems such as I'mRT MatriXX/Compass (IBA, Schwarzenbruck, Germany),[37,38] Math resolution (Math resolution, Columbia, MD),[26,34,35] and ArcCHECK-3DVH (Sun Nuclear, Melbourne, FL).[25]

The methodology used Compass/Boggula *et al*. and Math resolution/Rener *et al*., similar to the forward EPID dosimetry approach; here, ArcCHECK/Nelms *et al*. uses a perturbation technique rather than actual 3D dose calculation.[32,37] I'mRT MatriXX/Compass and Math resolution calculate the dose from the detector-measured fluence using the first principle. Compass uses a collapsed cone convolution/superposition algorithm, whereas Math resolution uses a Monte Carlo point spread function generated pencil beam dose calculation algorithm.[33,37]

The demerit of I'mRT MatriXX/Compass is with regard to the installation, which is time-consuming, labor intensive and complex. It is equivalent to the installation of a planning system with a substantial amount of data measurement and modeling of the data to create a correlation between TPS and compass calculation. For Rener *et al*., the compatibility of the dose calculation algorithm between TPS and Map resolution is a challenge because no modern planning system uses a pencil beam algorithm. The most popular technique is ArcCHECK-based measurement and 3DVH-based dose reconstruction; it does not require additional measurement for QA system installation. The advantage of ArcCHECK is a couch stationary detector system; it accurately represents the patient directional dependency (left–right). Meanwhile, I'mRT MatriXX can be used as both gantry stationary and couch stationary detector system; if used as a gantry stationary detector system it does not comprehend the directional dependency.[9]

The method described by Nelms *et al*. does not calculate the 3D dose from the ArcCHECK measured fluence. This methodology requires dose error, called as planned dose perturbation technique, between the TPS plan and measured fluence. Fluence was measured in an ArcCHECK phantom in a dose correction map; it is manipulated mathematically to generate a 3D dose error grid for the respective subset of beams/segments and is applied onto the TPS dose map.[25] The resulting corrected dose map is similar to a "virtual measurement" based 3D dose reconstructed inside the patient anatomy. However, the reconstruction of dose from the measured fluence is not based on the first principle. The demerit of such a method is that it is highly dependent on the dose planes, which are used as the references for the dose perturbation. The dose plans are obtained from ArcCHECK, a homogeneous cylindrical diode array; hence, the measured dose planes do not offer any heterogeneous fluence. This homogeneous measured dose planes are used as the base for perturbing the TPS calculated dose; hence, it offers good agreement between the calculated and measured dose.

The advantage of our 3D EPID dose reconstruction technique is as follows: it does not require additional software or hardware such as Compass/3DVH and I'mRT MatriXX/ArcCHECK. Our technique can be executed with the available elementary facility of the EPID panel and a TPS. The disadvantage of our technique is that in its present form, it is highly laborious and time-consuming. However, we are attempting to automate the process and hope to achieve and present in the future studies; we have extended the process for volumetric modulated arc therapy (VMAT) technique as well and are presently recruiting patients in this study.

Our technique is free from assumption or approximation in terms of dose calculation as it uses the same planning system. In general, EPID-based or other 3D dose reconstruction technique requires a few assumptions. For example, Wendling *et al*. approximated (not measured from first principle) the scatter component. In 3DVH measurement, it is considered that the error occurring during the beam delivery to ArcCHECK is the final error; the TPS dose is perturbed on the basis of this error.[2,19,25] These assumptions and approximation caused the EPID dosimetry (and cylindrical array measurements) to fail in the presence of the large heterogeneities or the 3D dose reconstruction to become undependable in a few instances.

The key factors influencing the discrepancy between TPS calculated and 3D or 2D reconstructed dose from EPID (or another detector)-measured fluence are as follows: (1) All the detectors, including EPID, are homogenous and hence fail to reproduce the true patient heterogeneities[39] and (2) the difference in the dose calculation algorithm between the TPS and 3D dose reconstruction modules.[19,33] These two factors are addressed in our study. Two salient features of our technique are the use of TPS generated heterogeneity correction (F_{het}), which represents a true patient scattering contribution, and the use of the same dose calculation algorithm between the treatment plan calculation in TPS and 3D dose reconstruction from EPID-measured fluence.

Any kernel-based algorithm calculated dose is the product of beam attenuation, scattering and inverse square law integrated over a radiological path length. In our study, F_{het} represents the final product of this integral in a patient; it accounts for the heterogeneity in the beam path. EPID is inherently a homogenous dose calculation medium; hence, it requires an additional heterogeneity correction to represent the true scattering condition. This is contributed by F_{het} in the present study. Incorporating F_{het} in the EPID dose calculation accounts for the heterogeneities and increases the efficiency of the EPID-based dose reconstruction by bridging the difference between the TPS and EPID. The other aspect of discrepancy between the TPS and EPID, i.e., the incompatibility of the dose calculation algorithm, is also successfully addressed by our technique.

Conclusion

We described a novel-EPID based pretreatment QA technique that functions effectively in the presence of large heterogeneities. This new technique accounts for the heterogeneity correction by reproducing a TPS-like condition by considering attenuation, scattering, inverse square law, and radiological path length. Furthermore, the incompatibility of the dose calculation algorithm between TPS and EPID-based 3D dose reconstruction is also successfully addressed.

Although the technique in the present study is limited to the fixed beam IMRT, work is in progress to extend it to VMAT and transit dosimetry.

Financial support and sponsorship

Nil.

Conflicts of interest

There are no conflicts of interest.

References

1. van Elmpt WJ, Nijsten SM, Schiffeleers RF, Dekker AL, Mijnheer BJ, Lambin P, *et al.* A Monte Carlo based three-dimensional dose reconstruction method derived from portal dose images. Med Phys 2006;33:2426-34.
2. Wendling M, Louwe RJ, McDermott LN, Sonke JJ, van Herk M, Mijnheer BJ, *et al.* Accurate two-dimensional IMRT verification using a back-projection EPID dosimetry method. Med Phys 2006;33:259-73.
3. Ju SG, Ahn YC, Huh SJ, Yeo IJ. Film dosimetry for intensity modulated radiation therapy: Dosimetric evaluation. Med Phys 2002;29:351-5.
4. Sarkar B, Ghosh B, Sriramprasath SM, Mahendramohan S, Basu A, Goswami J, *et al.* Optimized point dose measurement for monitor unit verification in intensity modulated radiation therapy using 6 MV photons by three different methodologies with different detector-phantom combinations: A comparative study. J Med Phys 2010;35:144-50.
5. Amerio S, Boriano A, Bourhaleb F, Cirio R, Donetti M, Fidanzio A, *et al.* Dosimetric characterization of a large area pixel-segmented ionization chamber. Med Phys 2004;31:414-20.
6. Mijnheer B, Georg D. ESTRO Booklet No. 9: Guidelines for the Verification of IMRT; 2008.
7. Greer PB, Popescu CC. Dosimetric properties of an amorphous silicon electronic portal imaging device for verification of dynamic intensity modulated radiation therapy. Med Phys 2003;30:1618-27.
8. Manikandan A, Sarkar B, Holla R, Vivek TR, Sujatha N. Quality assurance of dynamic parameters in volumetric modulated arc therapy. Br J Radiol 2012;85:1002-10.
9. Manikandan A, Sarkar B, Nandy M, Sureka CS, Gossman MS, Sujatha N, *et al.* Detector system dose verification comparisons for arc therapy: Couch vs. gantry mount. J Appl Clin Med Phys 2014;15:4495.
10. Van Esch A, Depuydt T, Huyskens DP. The use of an aSi-based EPID for routine absolute dosimetric pre-treatment verification of dynamic IMRT fields. Radiother Oncol 2004;71:223-34.
11. Berry SL, Sheu RD, Polvorosa CS, Wuu CS. Implementation of EPID transit dosimetry based on a through-air dosimetry algorithm. Med Phys 2012;39:87-98.
12. van Zijtveld M, Dirkx ML, de Boer HC, Heijmen BJ 3D dose reconstruction for clinical evaluation of IMRT pretreatment verification with an EPID. Radiother Oncol 2007;82:201-7.
13. van Elmpt WJ, Nijsten SM, Dekker AL, Mijnheer BJ, Lambin P. Treatment verification in the presence of inhomogeneities using EPID-based three-dimensional dose reconstruction. Med Phys 2007;34:2816-26.
14. van Elmpt W, McDermott L, Nijsten S, Wendling M, Lambin P, Mijnheer B. A literature review of electronic portal imaging for radiotherapy dosimetry. Radiother Oncol 2008;88:289-309.
15. Partridge M, Ebert M, Hesse BM. IMRT verification by three-dimensional dose reconstruction from portal beam measurements. Med Phys 2002;29:1847-58.
16. Van Uytven E, Van Beek T, McCowan PM, Chytyk-Praznik K, Greer PB, McCurdy BM. Validation of a method for *in vivo* 3D dose reconstruction for IMRT and VMAT treatments using on-treatment EPID images and a model-based forward-calculation algorithm. Med Phys 2015;42:6945-54.
17. Louwe RJ, Damen EM, van Herk M, Minken AW, Törzsök O, Mijnheer BJ. Three-dimensional dose reconstruction of breast cancer treatment using portal imaging. Med Phys 2003;30:2376-89.
18. Pecharromán-Gallego R, Mans A, Sonke JJ, Stroom JC, Olaciregui-Ruiz I, van Herk M, *et al.* Simplifying EPID dosimetry for IMRT treatment verification. Med Phys 2011;38:983-92.
19. Wendling M, McDermott LN, Mans A, Olaciregui-Ruiz Í, Pecharromán-Gallego R, Sonke JJ, *et al.* In aqua vivo EPID dosimetry. Med Phys 2012;39:367-77.
20. Mijnheer B, Beddar S, Izewska J, Reft C. *In vivo* dosimetry in external beam radiotherapy. Med Phys 2013;40:70903.
21. Olaciregui-Ruiz I, Rozendaal R, Mijnheer B, van Herk M, Mans A. Automatic *in vivo* portal dosimetry of all treatments. Phys Med Biol 2013;58:8253-64.
22. Olaciregui-Ruiz I, Rozendaal R, van Oers RFM, Mijnheer B, Mans A. Virtual patient 3D dose reconstruction using in air EPID measurements and a back-projection algorithm for IMRT and VMAT treatments. Phys Med 2017;37:49-57.
23. Boellaard R, Essers M, van Herk M, Mijnheer BJ. New method to obtain the midplane dose using portal *in vivo* dosimetry. Int J Radiat Oncol Biol Phys 1998;41:465-74.
24. Boellaard R, van Herk M, Uiterwaal H, Mijnheer B. First clinical tests using a liquid-filled electronic portal imaging device and a convolution model for the verification of the midplane dose. Radiother Oncol 1998;47:303-12.
25. Nelms BE, Simon WE, Sun Nuclear Corp. Radiation Therapy Plan dose Perturbation System and Method. United States Patent US, No. 7,945,022; 2011.
26. Renner WD. Radiation Therapy Dosimetry Quality Control Process. United States Patent US, No. 6,853,702; 2005.
27. 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.
28. Alhazmi A, Gianoli C, Neppl S, Martins J, Veloza S, Podesta M, *et al*. A novel approach to EPID-based 3D volumetric dosimetry for IMRT and VMAT QA. Phys Med Biol 2018;63:115002.
29. McCowan PM, Asuni G, van Beek T, van Uytven E, Kujanpaa K, McCurdy BM. A model-based 3D patient-specific pre-treatment QA method for VMAT using the EPID. Phys Med Biol 2017;62:1600-12.
30. Spreeuw H, Rozendaal R, Olaciregui-Ruiz I, González P, Mans A, Mijnheer B, *et al*. Online 3D EPID-based dose verification: Proof of concept. Med Phys 2016;43:3969.
31. Varian-Medical-Systems Eclipse Algorithms Reference Guide. Available from: https://www.varian.com/oncology/products/software/treatment-planning/eclipse-treatment-planning-system. [Last accessed on 2019 Jun 20].
32. 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;63:25008.
33. Renner WD, Sarfaraz M, Earl MA, Yu CX. A dose delivery verification method for conventional and intensity-modulated radiation therapy using measured field fluence distributions. Med Phys 2003;30:2996-3005.
34. Renner WD, Norton K, Holmes T. A method for deconvolution of integrated electronic portal images to obtain incident fluence for dose reconstruction. J Appl Clin Med Phys 2005;6:22-39.
35. Siebers JV, Kim JO, Ko L, Keall PJ, Mohan R. Monte Carlo computation of dosimetric amorphous silicon electronic portal images. Med Phys 2004;31:2135-46.
36. Storchi P, Woudstra E. Calculation of the absorbed dose distribution due to irregularly shaped photon beams using pencil beam kernels derived form basic beam data. Phys Med Biol 1996;41:637-56.
37. Boggula R, Lorenz F, Mueller L, Birkner M, Wertz H, Stieler F, *et al*. Experimental validation of a commercial 3D dose verification system for intensity-modulated arc therapies. Phys Med Biol 2010;55:5619-33.
38. Boggula R, Birkner M, Lohr F, Steil V, Wenz F, Wertz H. Evaluation of a 2D detector array for patient-specific VMAT QA with different setups. Phys Med Biol 2011;56:7163-77.
39. Arjunan M, Sekaran SC, Sarkar B, Manikandan S. A homogeneous water-equivalent anthropomorphic phantom for dosimetric verification of radiotherapy plans. J Med Phys 2018;43:100-5.