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Pre-treatment Verification Performed with Electronic Portal Imager Device (EPID) and IMatriXX for 204 Cancer Patients Treated with Intensity Modulated Radiotherapy (IMRT) – Phantom Based Study

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ABSTRACT

Introduction: State-of-art radiotherapy technique as Intensity Modulated Radiotherapy (IMRT) and Volumetric Modulated Arc Therapy (VMAT) are being used to treat cancer with high accuracy. Verification of planned and delivered dose distribution is critical; in this study we evaluated quality assurance (QA) results and effectiveness of Electronic Portal Imaging Device (EPID) and IMatriXX.

Material and Methods: Performance of EPID and IMatriXX was assessed with dose measurements using ionization chamber. Calibrated IMatriXX and EPID are used for pre-treatment patient-specific quality assurance (PSQA) for 204 patients plans with IMRT treatment technique on LINAC. Dose image were compared for gamma evaluation (3%/3mm) and combination of three scalar parameters were assessed against EPID to quantify gamma results within region of interest; namely average $\gamma(\gamma_{avg})$, maximum $\gamma(\gamma_{max})$ and Area $Gamma_{<1}$.

Results: The γ correlation comparisons yielded an average correlation of 0.991 for IMatriXX and 0.978 for EPID. The maximum gamma value is 0.99, while the minimum gamma is 0.872 for IMatriXX and 0.926 for EPID, which can be used as baseline. Our result suggests that EPID dosimetry, provides lower gamma correlation values than IMatriXX. Students Unpaired *t*-Test analysis was applied to two data sets. The calculated *p*-value 0.001 shows good correlation.

Conclusion: The EPID and IMatriXX have significantly improved dosimetric properties, providing more sensitive, accurate pre-treatment PSQA. The result shows EPID can replace other 2D dosimetry methods and ionization chamber measurements. It's an efficient, sensitive and accurate dosimetry tool and is primary protocol of pre-treatment quality assurance.

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Introduction

The dose verification methods are a part of advanced treatment techniques like Intensity Modulated Radiotherapy (IMRT) in radiotherapy. Commercially available Amorphous Silicon Electronic Portal Imager Device (a-Si EPIDs) are mainly used for patient setup verification before actual treatment and for dosimetry purposes i.e. verification of treatment plans.

Authors have reported that for verification of newer techniques in radiotherapy, EPIDs are useful [1-6]. Dose-response characteristics of EPID show that pixel signals are linear with dose and can be converted into absolute dose. EPID response is about ±0.5% over a long time, when there is no mishap in electronic parts [7,8].

Intensity-modulated radiotherapy (IMRT) dose distribution verification needs quality assurance (QA) tools of dosimetry in two dimensions. We know the usefulness of an EPID and IMatriXX over the film for IMRT fluence verification. EPID and IMatriXX measurements are simple to perform and require minimum setup. The EPID is mounted to Linear Accelerator (LINAC) gantry and it has the advantage of higher resolution and no additional hardware required for imaging and dosimetry. We can repeat these measurements easily and digital data is obtained quickly, but dosimetry films have the advantage of spatial resolution and it requires more time for developing and digitizing. Every new film batch requires a calibration curve to be generated before its use for dosimetry [9].

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After the calibration of EPID and IMatriXX for Linear Accelerator (LINAC) Varian Clinac DBX (Varian Medical Systems Palo Alto, USA) and for particular energy of 6MV, EPID images can be instantly converted into absolute dose images or portal dose image (PDI) [10].

Quantification, Recording and storage of QA measurements are more efficient when images are available in digital form. Medical physics departments require digitizing medical image data, hence film dosimetry is becoming more scarce and thus alternative measurement device systems will be needed for radiotherapy dose verification purposes [11].

Investigator has used the placing of detector inside a phantom [12], and other used EPID dose images measured at the detector plane. These EPID images are used to reconstruct the dose in a treatment plane or in the phantom or patient. Studies have reported the prospect of using an a-Si EPID for verification of IMRT treatment fields [13-17].

The commissioning of LINAC and Treatment Planning System (TPS - Eclipse version 11.0), was performed for clinical use. The inverse planning technique IMRT, was implemented for cancer patients in this rural center, where most other dosimetry equipments are not available. The treatment plans were created with five field plans for Brain, seven field plans for pelvis cases, nine field plans for Head and Neck tumor, and a dynamic Multi-Leaf Collimator (dMLC). The complex head and neck plans require nine fields which get splits into 18 fields during delivery.

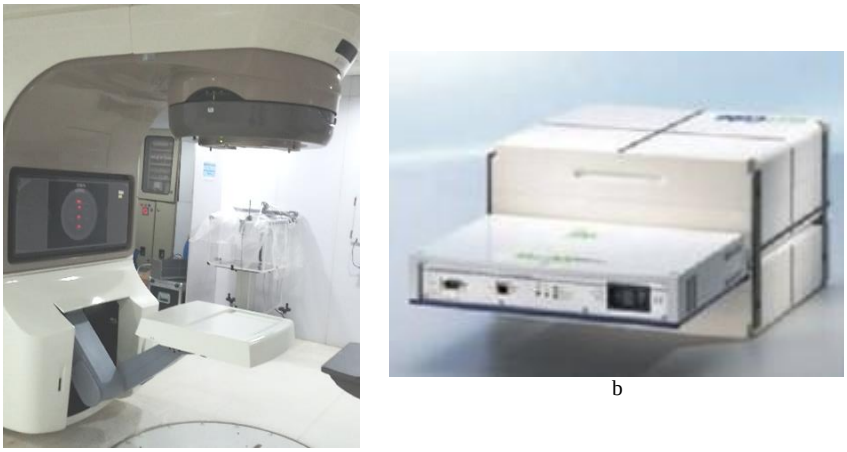
To verify the planned and delivered dose in dynamic IMRT treatment technique with accurate and efficient means is the demand of the clinic; hence we designed this study intending to demonstrate how IMatriXX and EPID dosimetry system can be used effectively for routine pre-treatment PSQA in cancer patients and further to study the sensitivity of gamma criteria. In a cancer center with no advanced 3D dose verification method, this study can set baseline values for plan verification.

Materials and Methods

EPID & IMatriXX Phantom dosimetry

In radiotherapy dosimetry, the gold standard is therapy verification films and a calibrated ionization chamber for dosimetry. LINAC's initial calibration was carried out with ion chamber 0.125cc and 0.6cc (IBA Dosimetry, Germany) in a water phantom as it is gold standard in radiation dosimetry.

The IMatriXX (IBA Dosimetry, Germany) device uses 1020 vented ion chambers arranged in a 32 x 32 array grid, with an active measurement area of 24.4 x 24.4 cm^2. The spatial resolution i.e. lateral spacing between two ion chambers is 7.62 mm. The dosimetry device, amorphous silicon (a-Si) flat-panel imager EPID aSi1000 (Varian Medical Systems, Palo Alto, USA) is having a 30 x 40 cm2 detection area with 768 x1024 pixels, phosphor screen, 1.0mm Cu build-up layer and hydrogenated *a*-Si:H photodiode array [18]. The spatial resolution of EPID is 0.391mm and detailed specifications are tabulated in Table 1 and the setup used for measurement is as shown in figure 1.



a b

Figure 1. Linear Accelerator (a) with a-Si EPID (b) IMatriXX phantom

Table 1: the detailed specifications of EPID and ImatriXX

Particulars / Dosimetry Devices	EPID		IMatriXX
Detector material	a-Si 1000	a-Si 1200	Ion Chamber Array
Max irradiated area (cm2)	30 × 40	43 × 43	30 x 30
Active area (cm2)	30 x 40	40 x 40	24.4 x 24.4
Active dosimetry matrix	768 × 1024	1190 × 1190	1020 Ion Chambers
Resolution /Pixel size (mm)	0.391	0.336	7.62

Patient treatment plans

IMRT treatment plans were analyzed for the 204 cancer patients planned with Eclipse Treatment Planning System (TPS) version 11.0 (Varian Medical Systems Palo Alto, CA). For all 204 patient's treatment plans, a five, seven or nine field dynamic IMRT technique was generated with prescription to planning target volume (PTV) dose and subsequently treated for various sites as seen in figure 2.

The treatment plans were optimized to achieve the prescribed dose to the PTV and better sparing of OARs viz. parotids, spine, lens, rectum, oral cavity etc. IMRT plan done with seven to nine fields, appropriate OAR and target priorities and the dose calculation grid of $0.25cm^3$ resolution is used for plan optimization. The maximum prescribed dose to the PTV was 74 Gy, given in 37 treatment fractions. The dynamic IMRT treatment plan was delivered with 6 MV photon beams.

The verification plans were generated for each treatment approved plan and EPID aSi1000 and IMatriXX ion chamber array. The basic calibration of EPID and IMatriXX for portal dosimetry and 2D dose verification respectively at the plane of iso-center was already performed. The gantry angle was set to 0° for both IMatriXX and EPID measurements and phantom position is fixed for all measurements.

All fluence map images were acquired using an amorphous silicon flat-panel imager EPID *a*-Si 1000. Images are processed at a lower resolution of 256x256 pixels. The calibration procedure that converts EPID pixel values to absolute dose (Gy) at the reconstruction plane for each beam are described in earlier studies [19, 20].

The intersection of the plane perpendicular to the beam axis and rotates at all relevant gantry angles is mid-plane. The reconstruction of dose in mid-plane of patient or phantom using TPS is like the dose calculated in a medium. The pixels from the sensitivity matrix collect the dose information used to account for relative deviation in the response between pixels over the total active area of EPID.

For each plan the plane of measurement corresponds to the EPID dose reconstruction plane. A mid-plane dose image was reconstructed; each field's EPID mid-plane dose image is the sum of all segments dose image. The verification plan created in TPS were compared with the measured 2D dose distribution in 'X' and 'Y' plane. EPID acquired fluence images were compared to the verification plan created in TPS in two dimensions at the mid-plane, perpendicular to the beam's axis.

Gamma images were evaluated with global 3% / 3 mm criteria and absolute dose profiles. The treatment plan is acceptable if, for verification plan, $\gamma_{avg} = 0.50$, $\gamma_{max} = 3.5$, and Area $Gamma_{<1} > 95\%$ as tolerance limits and IMatriXX correlation > 95%. Combining the above parameters gives a detailed and informative outline of the general agreement between planned and measured 2D fluence distributions for these 204 patient plans.

Methods of dose-comparison

Dose distributions were evaluated using software 'Portal Dosimetry' a workspace within ECLIPSE (Ver 11.0, Varian Medical, Palo Alto USA) and IMatriXX - OmniPro software (version 1.7 IBA Dosimetry, Germany). Using this software, the user can compare dose values obtained with EPID, IMatriXX, and the verification plan created from the treatment plan. Dose differences are calculated for points and 'X' and 'Y' profiles, and 2D distributions using a difference in images and the gamma evaluation method [21, 22, 23].

By defining the region of interest (ROI) user can quantify each verification plan with the help of three scalar parameters. The results are tabulated with IMatriXX correlation, maximum γ (γmax), average gamma (γ avg) and Area Gamma < 1 i.e. percentage of points with γ<1 [24, 25].

With Portal Dosimetry images, we get fluence which is not comparable to ionization chamber measurements. The EPID software gives Calibrated Units (CU) instead of dose and during calibration, one can set it as 1CU corresponding to 1 Gray (Gy).

To evaluate results, authors in earlier published data have used criteria of 2%/2 mm [26, 27], but also suggested that a relaxed criterion of 3% / 3mm can be used to include uncertainties. The gamma criteria of 3% global dose difference and 3mm distance to an agreement were used. During TPS dose calculations, uncertainties like calculation accuracy, reproducibility and devices used for calibration and measurement affect results [28, 29].

In 204 patients, statistical calculations showed that the patient-averaged gamma value is 0.24 ± 0.10 (1 SD) with EPID, while using 3% global dose / 3 mm as reference criteria for quantification of pre-treatment verification. The results show overall agreement between measured and predicted Portal Dose Images. The p-value corresponds to the level of statistical significance in the difference between the results for EPID & IMatrix using the student's t-test.

Students Unpaired't' Test analysis is applied for comparison to two data sets. 'p' value was set at 0.005. The calculated p value is = 0.001, which shows a good correlation between measured data with IMatriXX and EPID.

Results

A total of 204 patients of various cancer sites were planned for IMRT treatment, and plans were verified using EPID and IMatriXX. Out of these 204 patients, 128 were male and 76 Female.

The maximum number of patients were from the age group of 61yrs - 70yrs, with the maximum dose planned for treatment is 74 Gy for carcinoma of the Head and Neck and Pelvis, as shown in figure 3.

IMRT treatment Plans for 204 cancer patients were verified at the isocenter plane using aSi-1000 EPID measurement and IMatriXX measurement and analyzed using software ECLIPSE and OmniPro, respectively.

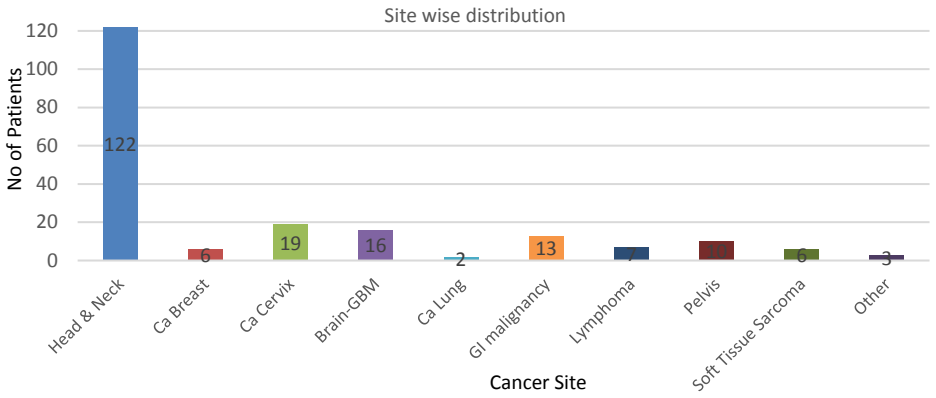


Figure 2. The site wise distribution of patients in each category in this rural setup of Maharashtra

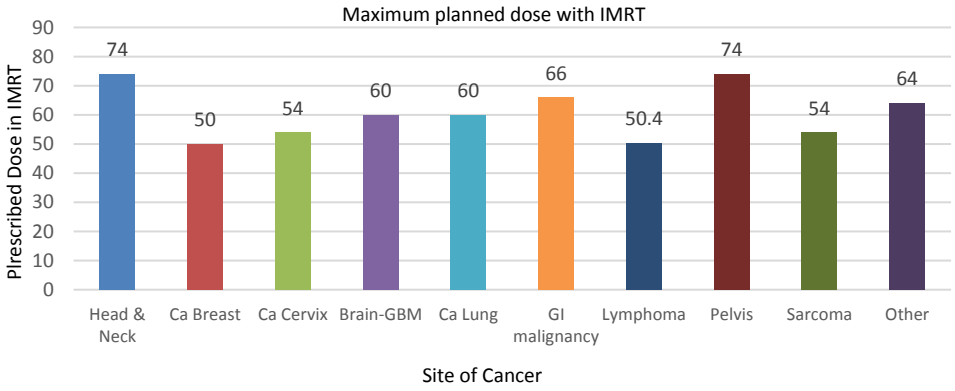
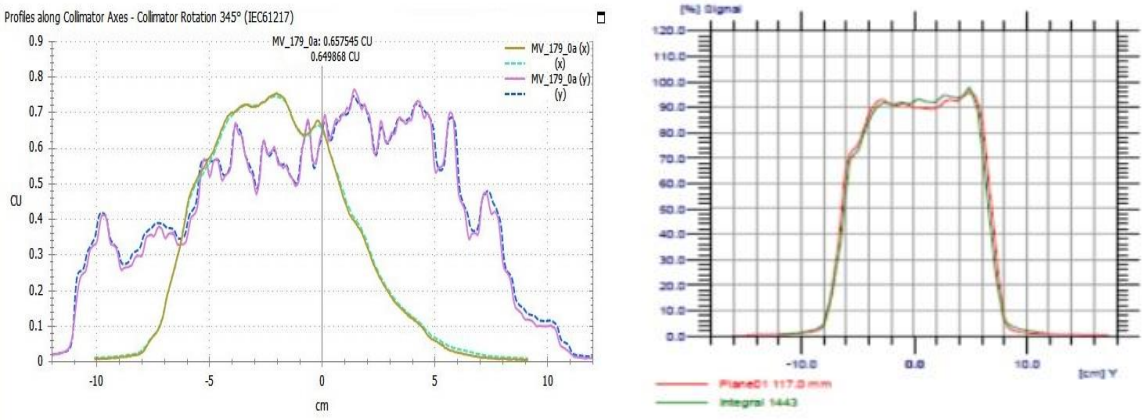


Figure 3. The maximum planned dose with IMRT treatment technique in each category.



(a) (b)

Gamma (3.0%, 3.0mm)	Value	Tol.	Abs.Dose Difference	Value
Area Gamma < 1.0	99.9 %	95.0 %	Max. Dose Difference	0.12 CU
Maximum Gamma	1.77	3.50	Avg. Dose Difference	0.01 CU
Average Gamma	0.20	0.50	Area Dose Diff > 0.50 CU	0.0 %
Area Gamma > 0.8	0.4 %		Area Dose Diff > 0.80 CU	0.0 %
Area gamma > 1.2	0.0 %		RESULT	PASSED

Figure 4. Comparison of predicted fluence and measured fluence with (a) portal dosimetry workspace in ECLIPSE TPS (b) IMatriXX – OmniPro, the planned fluence curve is displayed in both figures.

Table 2. Details of the Gamma analysis with acceptance criteria and the actual analysis

Site_Diag	No. of Patients	Imatrix-Correlation	Imatrix-Histogram	Area Gamma <1 (Tol=95%)	Max Gamma (Tol=3.50)	Avg Gamma (Tol = 0.5)
Head & Neck	122	0.992	91.80	97.90	2.283	0.196
Ca Breast	6	0.995	95.60	94.93	3.017	0.217
Ca Cervix	19	0.996	96.58	97.42	2.478	0.200
Brain-GBM	16	0.993	96.65	97.88	2.223	0.184
Ca Lung	2	0.997	96.00	96.55	2.895	0.205
GI malignancy	13	0.997	95.04	94.51	3.675	0.252
Lymphoma	7	0.997	95.01	95.52	3.317	0.241
Pelvis	10	0.996	96.34	97.95	2.331	0.190
Sarcoma	6	0.996	98.98	97.84	2.557	0.243
Other	3	0.996	98.81	98.07	2.350	0.210

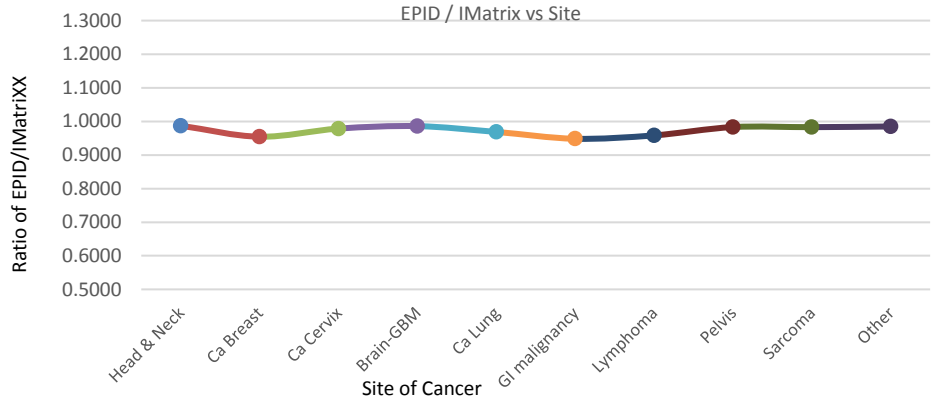


Figure 5. The ratio of EPID / IMatriXX vs. site, which reflects that, both the methods are equivalent for the plan comparison in a clinical setting.

EPID and IMatriXX 2D dose distributions for total of 204 patient plans were verified, these distributions agreed within the set criteria for all points within the image sets, with γ avg = 0.25 (0.05 SD), γ max = 2.71 and Area Gamma <1 = 96.86%. These values can be set as baseline values for this center during patient-specific quality assurance for cancer patients treated with IMRT. It was observed that as the Area Gamma$_{<1}$ decreases, as the value of γ_{avg} and γ_{max} increases, which indicates poor agreement between planned and measured 2D dose distribution with decreased IMatriXX correlation.

The measured value of the above parameters can be given by the example of Head and Neck (Table 2). If 97.90% of points of a field are contained by 3% and 3 mm, i.e. Area Gamma$_{<1}$ = 97.90%, and the γ_{max} value is 2.283, then a γ_{avg} value of 0.196 indicate a much better agreement with IMatriXX correlation of 99.2%. Figure 4 shows the comparison of the result of the Head and Neck patient treatment plan with EPID and IMatriXX phantom device. Some overresponse was observed in the doses measured for various field sizes at EPID and IMatriXX. The percentage difference is less than 3% with a dose difference of less than 2.0 cGy. The overresponse is due to the spatial resolution of IMatriXX and EPID as resolution of device has a great impact on the response for comparing dose distributions in steep dose gradient areas. For IMatriXX correlation = 0.995 and for EPID area gamma<1 is 96.86%, the over the response in IMatriXX is due to interpolation of values within ion chamber spacing of 7.62mm. Figure 5 shows that both the EPID and IMatriXX correlation can be compared in a clinical setting for cancer cases.

The observed area gamma<1 for breast carcinoma was 94.93%, and GI malignancy it was 94.51% which was the lowest among all other sites because in IMRT planning of breast and GI malignancy, stringent OAR constraints create more dose gradient regions with less number of treatment fields.

Disagreement is observed in 5 plans out of the 204 verification plans. All these 5 plans fail in a high dose gradient area, and errors exceeded the acceptance criteria. The IMatriXX correlation and Area Gamma < 1 are found to be. 81.5%, 91.6%, 89.5%, 88.4 and 87.2% which are less than acceptable criteria of 95.0 %.

After examining line profiles of these 5 plans with disagreement revealed the failure in high dose gradient regions that were 3.4% - 13.5% lower than the reference tolerance value of 95%. The treatment plan was performed again with modified plan parameters for these cases, which reduces high dose gradient regions and shows improved dose agreement between planned and measured fluence distributions.

The IMatriXX slightly overestimates the gamma correlation, as it has a resolution of 7.62 mm and

interpolates values between missing measurement points in dose image (TG-218) [30, 31], as seen from table 2 the IMatriXX correlation values are higher than that of EPID values.

Discussion

With the introduction of state-of-art radiotherapy treatment techniques as IMRT and VMAT for cancer treatment, the requirement for QA in radiotherapy has increased. The gold standard in Radiation Dosimetry is the use of calibrated ion chambers. For dose verification, in addition to ion chamber measurements, other techniques like EPID dosimetry are being used.

Authors have studied the dose-response characteristics of EPID and described its use in clinical dosimetry. As the EPID has higher sensitivity, the results of Portal dosimetry can persuade accurate dose delivery to patients to get better accuracy in treatment delivery [32, 33].

Pre-treatment evaluation for a large group of patients has been reported by other authors using film dosimetry and not by using EPID and IMatriXX. Stock et al [34] in this study author reported that the average gamma (γ avg) = 0.45 ± 0.10 when using 3% global dose/3 mm criteria. The results of this study are comparable with the study of Stock et al. which proves the sensitivity of gamma criteria for IMRT plan verification. This study shows the average gamma passing is 0.20 ± 0.05 with EPID while using 3% global dose / 3 mm criteria for an evaluation in the various site of carcinoma. Earlier studies show that iٹ other than 3% / 3mm, these values would be re-scaled as per new criteria.

Author Chang J. et al. [35] compared 25 IMRT plans reported that overall agreement was within 2%. The results of this study with mean gamma 0.19 and standard deviation of 0.05 are comparable to the present study, which suggests that EPID dosimetry is an effective tool for verification.

Van Zijtveld M. [36] revealed the pre-treatment verification for clinically relevant errors. It showed that the patient-averaged mean gamma value inside the field was 0.43 ± 0.13 (1 SD). The results of this study are comparable with the mean gamma value of 0.48 ± 0.19 (1 SD).

In 204 patients, statistical calculations showed that the patient-averaged gamma value is 0.24 ± 0.10 (1 SD) with EPID, while using 3% global dose / 3 mm as reference criteria for quantification of IMRT pre-treatment plan verification. The results show overall agreement between measured and predicted Portal Dose Images and IMatriXX correlation. The p-value corresponds to the level of statistical significance in the difference between the results for EPID & IMatriXX using the Student's unpaired t-test (IBM SPSS 16.0 Statistics). It is applied for comparison to two data sets. 'p' value was set at 0.005. Calculated p value is = 0.001, which shows good correlation between measured data with IMatriXX and EPID.

The gamma correlation result shows average correlation of 0.991 for IMatriXX and 0.978 for EPID. The observed maximum correlation for IMatriXX is 0.990 while for EPID it is 0.926. The present study suggests EPID dosimetry as QA tool having better sensitivity and effectiveness.

The time taken for dose measurement varies for various methods, depending on the equipment and software used. It is observed that measuring a digital EPID fluence image is always faster than other techniques of dose images measurements. In the absence of advanced 3D dosimetry techniques, EPID dosimetry can give confidence in beam delivery. The study shows that EPID has advantages over IMatriXX and can be efficiently used for IMRT plan verification. Thus, with appropriate calibration, EPID can serve as an efficient dosimetry tool in rural setup.

Conclusion

The verification of clinical IMRT plans before actual treatment to cancer patients using 2D portal dosimetry is very effective and helpful. The results of the 204 patients using 2D dosimetry suggest that it could replace other 2D dosimetry systems used in pre - treatment plan verification methods.

EPID has an advantage over other dosimetry devices like IMatriXX, because of its high resolution of 0.391mm. Our result suggests that EPID dosimetry, also called Portal Dosimetry, provides lower gamma correlation values than IMatriXX.

In radiation dosimetry, the use of therapy verification films and measurements using an ion chamber is considered the gold standard. The EPID shows close consistency with ion chamber measurement at the plane of the isocenter.

The treatment plan verification i.e. planned versus measured fluence distribution results of 2D dosimetry, are used to setup baseline values, which will be used for further dosimetry purposes. The sensitivity, efficiency and accuracy in measurement using EPID have demonstrated the usefulness of this dosimetry tool in pre-treatment quality assurance process.

References

1. El-Mohri Y, Antonuk LE, Yorkston J, Jee KW, Maolinbay M, Lam KL, Siewerdsen JH. Relative dosimetry using active matrix flat-panel imager (AMFPI) technology. Medical physics. 1999 Aug;26(8):1530-41..
2. McCurdy BM, Luchka K, Pistorius S. Dosimetric investigation and portal dose image prediction using an amorphous silicon electronic portal imaging device. Medical physics. 2001 Jun;28(6):911-24..
3. Grein EE, Lee R, Luchka K. An investigation of a new amorphous silicon electronic portal imaging device for transit dosimetry. Medical physics. 2002 Oct;29(10):2262-8..
4. Greer PB, Popescu CC. Dosimetric properties of an amorphous silicon electronic portal imaging device for verification of dynamic intensity modulated radiation therapy. Medical physics. 2003 Jul;30(7):1618-27.

5. Warkentin B, Steciw S, Rathee S, Fallone BG. Dosimetric IMRT verification with a flat-panel EPID. Medical physics. 2003 Dec;30(12):3143-55.
6. McDermott LN, Louwe RJ, Sonke JJ, Van Herk MB, Mijnheer BJ. Dose‐response and ghosting effects of an amorphous silicon electronic portal imaging device. Medical physics. 2004 Feb;31(2):285-95.
7. Louwe RJ, McDermott LN, Sonke JJ, Tielenburg R, Wendling M, Van Herk MB, Mijnheer BJ. The long-term stability of amorphous silicon flat panel imaging devices for dosimetry purposes: Stability of EPID response. Medical physics. 2004 Nov;31(11):2989-95.
8. Partridge M, Evans PM, Mosleh-Shirazi A, Convery D. Independent verification using portal imaging of intensity-modulated beam delivery by the dynamic MLC technique. Medical physics. 1998 Oct;25(10):1872-9.
9. Bucciolini M, Banci Buonamici F, Casati M. Verification of IMRT fields by film dosimetry. Medical physics. 2004 Jan;31(1):161-8.
10. Georg D, Kroupa B, Winkler P, Pötter R. Normalized sensitometric curves for the verification of hybrid IMRT treatment plans with multiple energies. Medical physics. 2003 Jun;30(6):1142-50.
11. Reiner BI, Siegel EL, Siddiqui K. Evolution of the digital revolution: a radiologist perspective. Journal of Digital Imaging. 2003 Dec 1;16(4):324-30.
12. Stock M, Kroupa B, Georg D. Interpretation and evaluation of the γ index and the γ index angle for the verification of IMRT hybrid plans. Physics in Medicine & Biology. 2005 Jan 12;50(3):399.
13. Jursinic PA, Nelms BE. A 2-D diode array and analysis software for verification of intensity modulated radiation therapy delivery. Medical physics. 2003 May;30(5):870-9.
14. Létourneau D, Gulam M, Yan D, Oldham M, Wong JW. Evaluation of a 2D diode array for IMRT quality assurance. Radiotherapy and oncology. 2004 Feb 1;70(2):199-206.
15. Wiezorek T, Banz N, Schwedas M, Scheithauer M, Salz H, Georg D, Wendt TG. Dosimetric Quality Assurance for Intensity‐Modulated Radiotherapy. Strahlentherapie und Onkologie. 2005 Jul 1;181(7):468-74.
16. Childress NL, Bloch C, White RA, Salehpour M, Rosen II. Detection of IMRT delivery errors using a quantitative 2D dosimetric verification system. Medical physics. 2005 Jan;32(1):153-62.
17. Lang S, Reggiori G, Puxeu Vaque J, Calle C, Hrbacek J, Klöck S, Scorsetti M, Cozzi L, Mancosu P. Pretreatment quality assurance of flattening filter free beams on 224 patients for intensity modulated plans: a multicentric study. Medical physics. 2012 Mar;39(3):1351-6.
18. Steciw S, Warkentin B, Rathee S, Fallone BG. Three-dimensional IMRT verification with a flat-panel EPID. Medical physics. 2005 Feb;32(2):600-12.
19. Wendling M, Louwe RJ, McDermott LN, Sonke JJ, van Herk M, Mijnheer BJ. Accurate two-dimensional IMRT verification using a back-projection EPID dosimetry method. Medical physics. 2006 Feb;33(2):259-73.
20. Low DA, Harms WB, Mutic S, Purdy JA. A technique for the quantitative evaluation of dose distributions. Medical physics. 1998 May;25(5):656-61.
21. Pulliam KB, Huang JY, Howell RM, Followill D, Bosca R, O' Daniel J, Kry SF. Comparison of 2D and 3D gamma analyses. Medical physics. 2014 Feb;41(2):021710.
22. Warkentin B, Steciw S, Rathee S, Fallone BG. Dosimetric IMRT verification with a flat-panel EPID. Medical physics. 2003 Dec;30(12):3143-55.
23. Winkler P, Zurl B, Guss H, Kindl P, Stuecklschweiger G. Performance analysis of a film dosimetric quality assurance procedure for IMRT with regard to the employment of quantitative evaluation methods. Physics in Medicine & Biology. 2005 Jan 25;50(4):643.
24. Childress NL, White RA, Bloch C, Salehpour M, Dong L, Rosen II. Retrospective analysis of 2D patient-specific IMRT verifications. Medical physics. 2005 Apr;32(4):838-50.
25. Budgell GJ, Perrin BA, Mott JH, Fairfoul J, Mackay RI. Quantitative analysis of patient-specific dosimetric IMRT verification. Physics in Medicine & Biology. 2004 Dec 16;50(1):103.
26. Partridge M, Symonds-Tayler JR, Evans PM. IMRT verification with a camera-based electronic portal imaging system. Physics in Medicine & Biology. 2000 Dec;45(12):N183.
27. Louwe RJ, Damen EM, Van Herk M, Minken AW, Törzsök O, Mijnheer BJ. Three-dimensional dose reconstruction of breast cancer treatment using portal imaging. Medical physics. 2003 Sep;30(9):2376-89.
28. Mancuso GM, Fontenot JD, Gibbons JP, Parker BC. Comparison of action levels for patient-specific quality assurance of intensity modulated radiation therapy and volumetric modulated arc therapy treatments. Medical physics. 2012 Jul;39(7Part1):4378-85.
29. Kry SF, Molineu A, Kerns JR, Faught AM, Huang JY, Pulliam KB, Tonigan J, Alvarez P, Stingo F, Followill DS. Institutional patient-specific IMRT QA does not predict unacceptable plan delivery. International Journal of Radiation Oncology* Biology* Physics. 2014 Dec 1;90(5):1195-201.
30. Miften M, Olch A, Mihailidis D, Moran J, Pawlicki T, Molineu A, Li H, Wijesooriya K, Shi J, Xia P, Papanikolaou N. Tolerance limits and methodologies for IMRT measurement-based verification QA: recommendations of AAPM Task Group No. 218. Medical physics. 2018 Apr;45(4):e53-83.
31. McKenzie EM, Balter PA, Stingo FC, Jones J, Followill DS, Kry SF. Toward optimizing patient-specific IMRT QA techniques in the accurate detection of dosimetrically acceptable and unacceptable patient plans. Medical physics. 2014 Dec;41(12):121702.
32. Chan MF, Li J, Schupak K, Burman C. Using a novel dose QA tool to quantify the impact of systematic errors otherwise undetected by conventional QA methods: clinical head and neck case studies. Technology in cancer research & treatment. 2014 Feb;13(1):57-67.
33. Childress NL, Rosen II. The design and testing of novel clinical parameters for dose comparison. International Journal of Radiation Oncology* Biology* Physics. 2003 Aug 1;56(5):1464-79.

34. Stock M, Kroupa B, Georg D. Interpretation and evaluation of the γ index and the γ index angle for the verification of IMRT hybrid plans. Physics in Medicine & Biology. 2005 Jan 12;50(3):399.
35. Chang J, Ling CC. Using the frame averaging of aS500 EPID for IMRT verification. Journal of applied clinical medical physics. 2003 Sep;4(4):287-99.
36. van Zijtveld M, Dirkx ML, de Boer HC, Heijmen BJ. Dosimetric pre-treatment verification of IMRT using an EPID; clinical experience. Radiotherapy and oncology. 2006 Nov 1;81(2):168-75.