International Journal of Medical Physics, Clinical Engineering and Radiation Oncology, 2025, 14(4), 161-181
https://www.scirp.org/journal/ijmpcero
ISSN Online: 2168-5444
ISSN Print: 2168-5436

Evaluating IMRT and VMAT Dose Verification: Capability Index Analysis for Quality Assurance in Radiotherapy

Ayman G. Ibrahim[1,2], Hesham S. El-Bahkiry[3,4], Ismail Emam[5], Osama Abbas[2,5], Doaa G. Mahmoud[2,6]

[1]Clinical Oncology and Nuclear Medicine Department, Mansoura University Hospitals, Mansoura, Egypt
[2]Oncolgy Department, Saudi German Hospital Aseer, Khamis Mushait, Saudi Arabia
[3]Clinical Oncology and Nuclear Medicine Department, Faculty of Medicine, Mansoura University, Mansoura, Egypt
[4]Diagnostic Radiography Technology Department, College of Nursing and Health Sciences, Jazan University, Jazan, Saudi Arabia
[5]Clinical Oncology Department, Faculty of Medicine, Ain Shams University, Cairo, Egypt
[6]Department of Clinical Oncology, Faculty of Medicine, Assiut University, Assiut, Egypt
Email: aymanstohy@yahoo.com, hsbahkiry@yahoo.com

How to cite this paper: Ibrahim, A.G., El-Bahkiry, H.S., Emam, I., Abbas, O. and Mahmoud, D.G. (2025) Evaluating IMRT and VMAT Dose Verification: Capability Index Analysis for Quality Assurance in Radiotherapy. *International Journal of Medical Physics, Clinical Engineering and Radiation Oncology*, **14**, 161-181.
https://doi.org/10.4236/ijmpcero.2025.144013

Received: October 23, 2025
Accepted: November 22, 2025
Published: November 25, 2025

Abstract

Introduction: Advanced radiotherapy methods include Intensity modulated radiotherapy (IMRT) and volumetric modulated arc therapy (VMAT) requiring stringent quality assurance (QA) to ensure accurate dose delivery. This study assesses the effectiveness of IMRT and VMAT dosage verification by gamma index analysis and capability index (C_{pml}), which are statistical process control (SPC) tools, to assess QA process reliability and compare dosimetrical outcomes for head and neck and rectal cancer treatment plans. **Materials and Methods:** For 28 cases of head and neck (14 IMRT and 14 VMAT) were generated utilizing treatment planning system (TPS) Eclipse, which delivered 6 MV photon beam linear accelerator (Varian, Clinac IX). Dose distributions were measured using an aSi-1000 electronic portal imaging device (EPID) and OCTAVIUS Detector 1500 2D array, compared against TPS calculations using gamma index criteria (3%/3 mm). Control charts and C_{pml} evaluated QA process stability for 25 cases. Dosimetrical comparisons for rectal cancer assessed planning target volume coverage, organ-at-risk doses, and monitor units. **Result:** For head and neck the gamma passing rates showed strong agreement, with means of 99.24% ± 0.37 (EPID) and 98.76% ± 0.61 (2D array) for IMRT, and 99.00% ± 0.38 (EPID) and 98.91% ± 0.43 (2D array) for VMAT. For rectal cancer the capability index (C_{pml}) values of 1.36 (IMRT) and 1.47 (VMAT) indicated optimal QA performance. VMAT plans for rectal cancer reduced

MUs and treatment time by approximately 50% while achieving comparable PTV coverage and OAR sparing. **Conclusion:** VMAT demonstrates efficiency advantages over IMRT, with robust QA processes, supported by SPC and capability index assessments, enhancing treatment precision and patient outcomes.

Keywords

IMRT, VMAT, EPID, 2D Array, Capability Index, Quality Assurance

1. Introduction

Radiation therapy is one of the most essential cancer treatment options. Methods of radiotherapy evolved from two dimensional radiation therapy (2DRT), 3D conformal radiation therapy (3D-CRT) to modern techniques like intensity modulated radiation therapy (IMRT) and volumetric modulated arc therapy (VMAT) [1] [2]. IMRT is an advanced technique of irradiation treatment plan that can be modulated by a moving multi-leaf collimator (MLC). IMRT has become a standard modality for highly delivered conformal of dose distribution compared to 3D conformal radiation therapy techniques (3D-CRT). VMAT is a comparatively new dose delivery method that allows highly conformal radiation distributions delivery in a short time and with minimal monitor units (MUs) as compared to IMRT [3]. At the same time, VMAT technique coordinates rotation of the gantry, MLC movement regularly and modification of dose rate [4]. Where the motion of the MLC modulates the radiation dose in the IMRT and VMAT procedures. Before beginning clinical therapy, program of quality assurance (QA) dose distribution is advised to confirm appropriate treatment delivery [5] [6]. Quality assurance (QA) is essential to decrease systematic errors in order to preserve the quality of a certain process [7]. The intricate nature of treatment demands enhanced dose verification systems and detailed quality assurance procedure reports in the planning of radiotherapy [8].

Statistical Process Control (SPC) tools provide a more comprehensive approach to quality assurance in modern radiotherapy compared to traditional pass/fail criteria. While simple thresholds can only indicate whether a parameter meets an acceptance limit, they fail to capture subtle variations or trends that may signal emerging issues in treatment delivery. By applying SPC methods in Microsoft Excel such as control charts, process capability analysis, and trend evaluation clinicians and physicists can monitor performance over time and distinguish between random fluctuations and systematic changes. This allows for early identification of deviations before they result in clinically significant errors, supports data-driven decision-making, and promotes continuous process improvement. In the complex and high-precision environment of radiotherapy, SPC therefore enhances both the reliability and safety of treatment delivery. The gamma index (γ) is a comparison of measured and calculated dose distribution for treatment plan.

Alongside dose difference (DD) and distance to agreement (DTA), it serves as a quantitative assessment tool for dosage distribution analysis [9]. Mohamed I. E. *et al.* studied the agreement between predicted and measured doses for different malignant tumors using various criteria of gamma, confirming VMAT QA with 2D array detector and EPID. Found that the criterion of gamma; 3%/3 mm was the best appropriate for VMAT plan QA [10]. Control chart is another essential tool in statistical process control (SPC), used to monitor process variation and distinguish between systematic and random errors in radiotherapy QA. Pawlicki *et al.* investigated its application in radiotherapy quality assurance [11]. Nordström F. *et al.* utilized control charts for monitor unit (MU) verification, demonstrating their effectiveness in patient-specific quality control and treatment site comparisons, with control limits aligned with AAPM TG114 guidelines [12]. Additionally, control charts were found to be effective for verification assessments in patient-specific quality assurance (QA) [10]. Further advancements include Rajasekaran D. *et al.*'s evaluation of the Octavius 4D system for VMAT QA, where they studied the relationship between gamma index analysis and plan complexity. Their findings revealed a strong relationship between beam complexity and gamma passing rates, isolating beam complexity effects from other dose error sources [13]. Roy A. *et al.* developed a framework of risk-adjusted control chart for IMRT plan evaluations, accounting for variations in patient and treatment-specific risk factors to guarantee strong quality control [14].

A Radiotherapy IMRT/VMAT Capability Index evaluates a department's readiness to verify complex dose deliveries utilizing VMAT and IMRT methods. As shown in **Table 1**, the index's assessment encompasses eight critical quality assurance domains. This index is widely used for internal audits, quality improvement programs, and justifying QA tool investments. Pawlicki *et al.* used capability indices and control charts for IMRT QA [15], while Sanghangthum T. *et al.* used statistical process control (SPC) to define gamma pass-rate control limits and evaluate the process capability index (C_{pml}) for IMRT/VMAT QA [16].

Table 1. The multidimensional assessment criteria of the capability index.

1	QA Hardware Availability	Phantom types (e.g., ion chamber, film, 2D/3D arrays, Arc Check, Delta4, etc.)	0 - 5
2	Software Tools	Use of advanced analysis tools (gamma index, DVH-based QA, log file analysis, AI-based QA)	0 - 5
3	Verification Coverage	QA performed for all patients, or high-risk plans only	0 - 5
4	Automation Integration	Use of automated workflows (scripted QA, report generation, integration with TPS)	0 - 5
5	Staff Training & Expertise	Number of staff trained in IMRT/VMAT QA protocols and software	0 - 5
6	Dose Calculation Verification	independent MU checks, 2nd dose engine, Monte Carlo, or log file-based dose reconstruction	0 - 5
7	Imaging & Motion QA	Capability for 4D QA, image guidance verification, MLC position QA	0 - 5
8	Continuous Improvement	Frequency of QA protocol review and implementation of findings from previous errors	0 - 5

Statistical Process Control (SPC) methods—recommended by AAPM Task

Groups—are increasingly adopted in radiotherapy QA to distinguish special-cause from routine variations in patient-specific QA, linac QA, and positional verification. Effective monitoring relies on proper tool selection (e.g., Shewhart/time-weighted control charts) and expertise [17]. Priya Jacob compared Portal Dosimetry (EPID/Eclipse TPS) and ArcCheck phantom for RapidArc/IMRT QA, reporting >98% (EPID) and >95% (ArcCheck) gamma-pass rates at 2%/2 mm, with EPID showing higher consistency due to embedded detectors [18]. Meanwhile, Webster M. *et al.* highlighted transformative advances like adaptive radiotherapy, AI-driven automation, particle therapy (proton/FLASH), and biological therapies (BNCT/radioimmunotherapy), which collectively enhance precision and personalization in cancer care [19].

This study demonstrates the comparison of dose distributions between radiotherapy treatment plans using a clinical case example. The primary objective is to generate clinically interpretable results to support medical decisions regarding plan modification or optimization of the reference treatment plan. The research aims to establish standardized gamma pass-rate criteria for patient-specific IMRT/VMAT QA across different tumor sites using control charts and assess the efficiency of the QA process through capability index (C_{pml}) analysis. By implementing statistical process control methods, the study provides medical physicists with quantitative tools to compare dosimetric outcomes of alternative treatment plans, objectively select optimal radiation treatment strategies, and enhance QA process reliability during therapy delivery.

2. Materials and Methods

The measurements in this work were performed utilizing a high-energy linear accelerator (Varian Clinac IX; Varian Medical Systems), 6 MV photon beams, at our department. *Portal Vision*: is amorphous silicon electronic portal imaging device (aSi-1000 EPID), It provides the resolution, and contrast of patient's images which enable verification and assurance of treatment quality, the dimension of 30 × 40 cm^2 with an array of 768 × 1024 detectors of amorphous silicon with dimensions of 0.392 × 0.392 mm^2. An aSi-1000 Portal Vision imager is a robotic support arm (Exact-Arm) and it was a part of the linear accelerator (linac.), contains a thin metal layer (1 mm copper), and a phosphor film of 0.5 mm. EPID calibration is related to calibration units (CU) and calibrated with field size 10 × 10 cm^2 and 100 MU, so that 1 CU equals to one MU delivered. The OCTAVIUS Detector 1500 is composed of a matrix of 1405 ion chambers arranged in a 27 × 27 cm^2 field. The detectors of plane-parallel measure 4.4 × 4.4 × 3 mm^3, center-to-center spacing of 7.1 mm. This system is integrated with VeriSoft software, allowing medical physicists to contrast the dose distributions in VMAT and IMRT verification plans generated by TPS Eclipse. The gamma index (γ) [9] [20] is a common method for assessing the measured dose distributions from detector systems against those calculated by the TPS. The dimensionless value for each point in the analyzed distribution is calculated using the dose difference (DD) and distance to agreement

(DTA) criteria. In quality assurance (QA), total percentage of points obtained area gamma ($\gamma_{\%\le 1}$), a pass/fail threshold was established for a certain DD/DTA criterion [21]-[23]. Agazaryan N. *et al.* performed a using an ion chamber for each composite plan of absolute dosimetry. The agreement between measurements and calculations had been observed. All of gamma parameters' means and standard deviations were computed and analyzed. The validity criteria were accepted with a gamma value of less than or equal to 1 ($\gamma_{\%\le 1}$) set at 97%. Three gamma scaling parameters: maximum γ ($\gamma_{\max}$), average γ (γ_{avg}), and the percentage of points meeting the gamma criteria ($\gamma_{\%\le 1}$) were assessed for each field, along with mean and the standard deviation. For every plan, the gamma criteria of 3%/3 mm were evaluated by a comparison of the calculated and computed dose distributions in radiotherapy [24].

2.1. Pre-Treatment QA of IMRT and VMAT for Head and Neck Cases

The gamma index (γ) was used to assess agreement between measurements and calculations. This study's test plans for 28 cases (14 IMRT and 14 VMAT), were produced using the treatment planning system (TPS) Eclipse Ver. 8.9 (Varian Medical Systems) and linear accelerator (Varian linac.). For IMRT plans, use 6 MV photon beam energy at 400 MU/min, whereas for VMAT plans, use the greatest dose rate via fast arc 600 MU/min. Two rapid arcs; (one clockwise (CW) and the other counterclockwise (CCW)) with a normal gantry range of 350˚ (from 185˚ to 175˚ for the CW rotation and from 175˚ to 185˚ for the CCW rotation) were used to carry out the rapid arc treatment plans using 6 MV photon energy. Fourteen IMRT plans for head and neck cases consisted of 102 IMRT fields. The IMRT and VMAT dose calculations using the Algorithm of Anisotropic Analysis (AAA) and portal dose estimates used to prepare the verification plans. In pretreatment, using the portal dose prediction method, we created IMRT or VMAT verification plans for portal dosimetry quality assurance. For comparison purposes, all verification plan calculations employed a 2.5 mm grid size. The portal dosimetry results were compared using an independent verification approach that utilized 2D array ion chamber and analysis software (VeriSoft software). All points of 2D array had a gamma index (γ) value, and the passing rate was the percentage of points with a gamma value ≤ 1 and meeting the DD% and DTA mm requirements. Pass rates of the dosimetry tools (EPID and 2D array) were compared using gamma criteria (3% DD/3 mm DTA).

Control chart: includes of upper control limit (*UCL*), centerline (*CL*), lower control limit (*LCL*), and points of data. The control chart is used to validate and control the method's variations. If the data is within the control limits, it will be under control even if the data changes randomly. If some data exceeds the control limits, systematic errors occur. Points of data beyond the control limits must be eliminated for the process to be under control again [24]-[26]. The percent gamma percentage of IMRT and VMAT quality assurance plans revealed variations in EPID measurement and Eclipse calculation, which are represented on an

X-control chart.

2.2. Process Capability Index

Is a quantitative method for analyzing process stability and capability throughout quality management program. The process capability index (C_{pml}) is used in the evaluation to describe a process's ability to generate data that meets the *LCL*. This index of (C_{pml}) is measure of the ability process within the specification limits [27] [28]. The capacity index is primarily used to measure the competency between the production tool and the quality aim for the product. In radiotherapy, production refers to the a-Si EPID as the detector tool, while product refers to the gamma value obtained because of patient-specific quality assurance activities. Process capability index was calculated using this Equation (1).

$$C_{pml} = \frac{\bar{x} - LCL}{1.46\sqrt{\sigma^2 + (\bar{x} - T)^2}} \tag{1}$$

Average of percentage gamma pass is denoted by $\bar{x}$, while σ is the standard deviation of percentage gamma pass. *LCL* is the lower specification limit $LCL = \bar{x} - 3\frac{\overline{mR}}{1.128}$, where $\bar{x}$, is the constant (1.128) [22] [29] and $\overline{mR}$ is the average percentage of gamma pass, and average moving range for all percentage gamma pass data. For a one-sided specification limit, the constant (1.46) is proposed [30]. T is the process's target value, which can be assumed to be the average of the gamma pass value when there is no target value (T = 0%). The capability index (C_{pml}) value greater than or equal to 1.33 indicates that the process is performing optimally [16]. Higher capability index (C_{pml}) value calculated, the higher is the efficiency of the process. Delivery was classified as a failure when the process capability index, C_{pml} was less than 1.33 [31]. The control limits for IMRT (177 fields) and VMAT (43 fields) were computed using the data points from the 25 cases. If there were out-of-control data points and we could identify the sources of error, they were eliminated. After that, control limits that were merely corrected for random errors were obtained by recalculating the centerline (*CL*) and control limits.

2.3. IMRT and VMAT Plan Comparison for Rectal Cancer

The rectal cancer cases represent a distinctly different anatomical region and treatment complexity from head and neck plans, allowing for a broader evaluation of the QA framework's applicability across varying clinical scenarios and enhancing the generalizability of the study's findings. Radiation therapy treatment plans for rectal cancer cases treated with IMRT and VMAT were compared. 5400 cGy was the recommended dosage, which was given in 28-fractions. A comparison was made between the dosimetrical data of IMRT and VMAT programs with 6 MV photon beam energy. The comparison included target volume, organs at risk (OAR) dose, and monitor units (MUs). The treatment plans were produced uti-

lizing IMRT and VMAT techniques. The IMRT plans included seven fields with various gantry orientations. The plans were computed utilizing the MLC delivery technology and the Eclipse treatment planning system (TPS) at Algorithm of Anisotropic Analysis (AAA). The VMAT plans used a single 360˚ arc, with gantry speed, MLC leaf position, and dose rate varying continually throughout delivery. IMRT or VMAT techniques were used to produce plans for each patient using photon beam energy 6 MV. Dose verification was performed using EPID to calculate the 2D gamma index and the percentage of area value of gamma is less than or equal to one ($\gamma_{\%\leq 1}$) used the gamma criteria (3%/3) mm. In radiotherapy treatment planning, the dose volume histogram (DVH) is a histogram that shows the relationship between the radiation dosage and tissue volume. DVHs are most typically used as a plan evaluation tool and to compare the doses from different plans. The dose volume histogram (DVH) was used to assess the planned target volume and normal organs.

3. Results and Discussion

Patient-specific quality assurance (QA) has become normal practice due to the intricate planning and prompt response of the sophisticated equipment used in modern radiation treatments. The IMRT and VMAT plans are regularly verified before treatment in the treatment center for processes that use 2D array and a-Si EPID. Our results found excellent agreement between calculated and measured dose distributions in all planes, with mean ± SD of gamma values. In the modern treatment techniques utilized in radiotherapy for the head and neck area are IMRT and VMAT. Some articles have compared the clinical efficacy of IMRT and VMAT treatment modalities. The dose distribution was smoothed out with VMAT and the treatment time was reduced. The dose conformance to the planned target volume (PTV) and dosage to normal tissues were equivalent across both techniques. Quality assurance (QA) results were significant and would be one of the criteria used to choose the technique. The doses calculated by TPS were contrasted with the doses measured by gamma evaluation (3%/3 mm) utilizing dosimetry instruments (2D array or EPID).

3.1. Pre-Treatment QA of IMRT and VMAT for Head and Neck Cases

For fourteen cases, the calculated dose using TPS via a gamma index (γ) with parameters of 3%/3 mm was compared with the measured dose plans. IMRT cases, Table 2 shows the gamma index findings for the 2D array ion chamber and EPID system analysis of the 102 IMRT fields. Table 3 displays the results of 14 VMAT plans (26 arc fields). All fields of the IMRT and VMAT plans were evaluated for mean and standard deviation (SD) of the average gamma (γ_{avg}), maximum gamma (γ_{max}), and the percentage of the area gamma value less than 1 ($\gamma_{\%\leq 1}$). A 2D array and EPID devices were used to compare the measured dose distributions for IMRT/VMAT plans with the TPS calculated distributions for 28 cases. Gamma index (γ) was used to analyze the quantitative distribution of calculated and meas-

ured doses. Gamma evaluation tolerance: area Gamma ≤ 1.0 = 97%, maximum Gamma = 3.50, and average Gamma = 0.50 [26]. The rate of gamma passes which were obtained by comparisons of results calculated in TPS and IMRT plans measured by 2D array detector system and Portal dosimetry (EPID) with different gamma criteria for area Gamma $\gamma_{\%\leq 1}$, maximum gamma (γ_{max}), and average gamma (γ_{avg}) are shown in Figures 1-3. The rate of gamma passes of VMAT plans obtained by comparison of 2D array and portal dosimetry (EPID) results calculated by TPS and measured dosimetry tools with different gamma criteria for area Gamma ($\gamma_{\%\leq 1}$), the maximum gamma (γ_{max}), and average gamma (γ_{avg}) are shown in Figures 4-6.

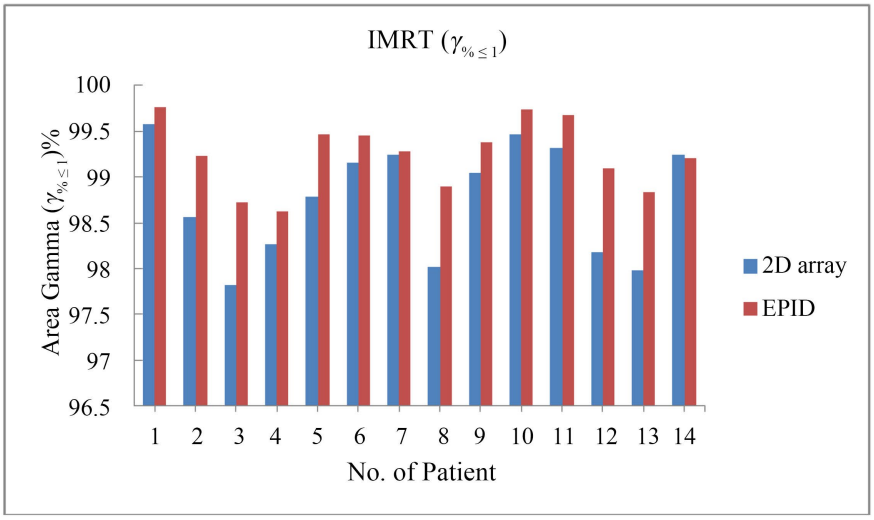


Figure 1. The gamma passed rates of IMRT obtained by comparison of 2D array and EPID results by TPS calculated and measured with different gamma criteria for area Gamma $\gamma_{\%\leq 1}$.

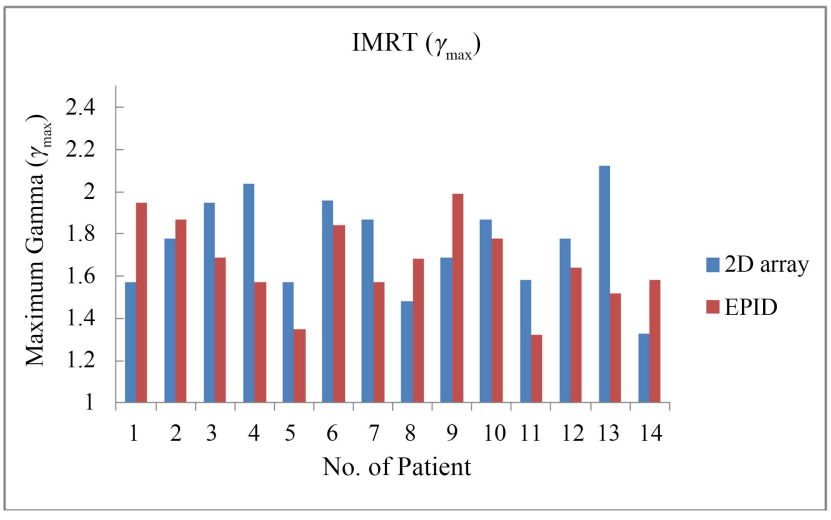


Figure 2. The gamma passed rates of IMRT obtained by comparison of 2D array and EPID results by TPS calculated and measured with different gamma criteria for maximum gamma (γ_{max}).

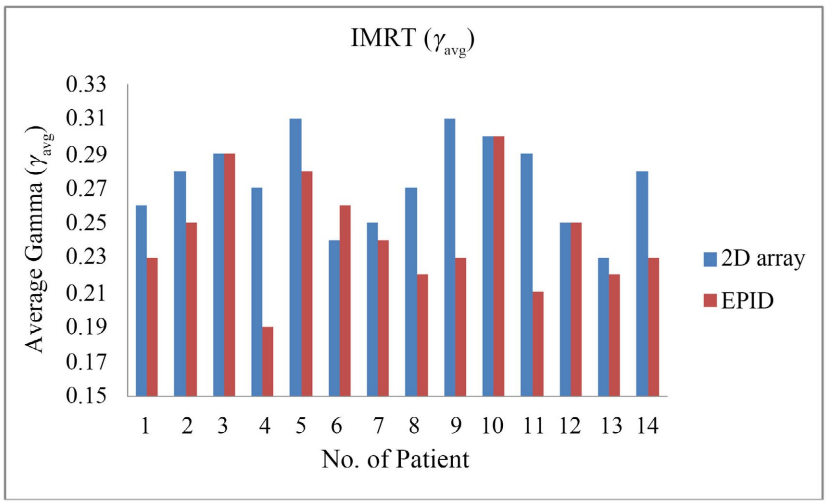


Figure 3. The gamma passed rates of IMRT obtained by comparison of 2D array and EPID results by TPS calculated and measured with different gamma criteria for average gamma (γ_{avg}).

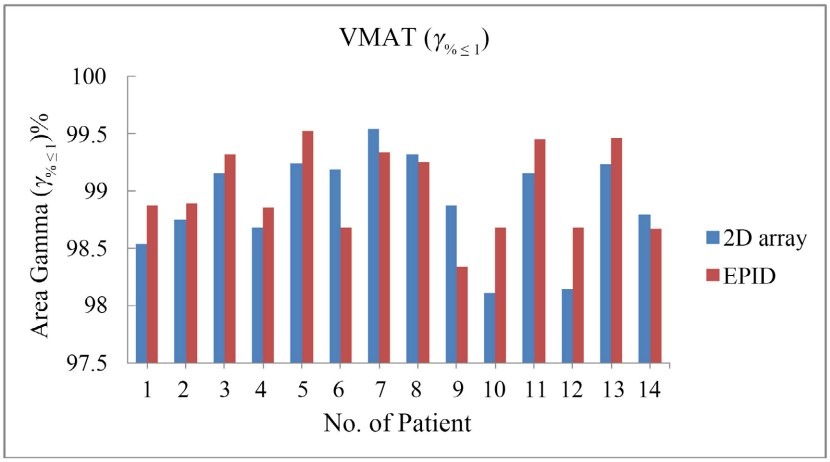


Figure 4. The gamma passed rates of VMAT obtained by comparison of 2D array and EPID results by TPS calculated and measured with different gamma criteria for area Gamma ($\gamma_{\%\leq 1}$).

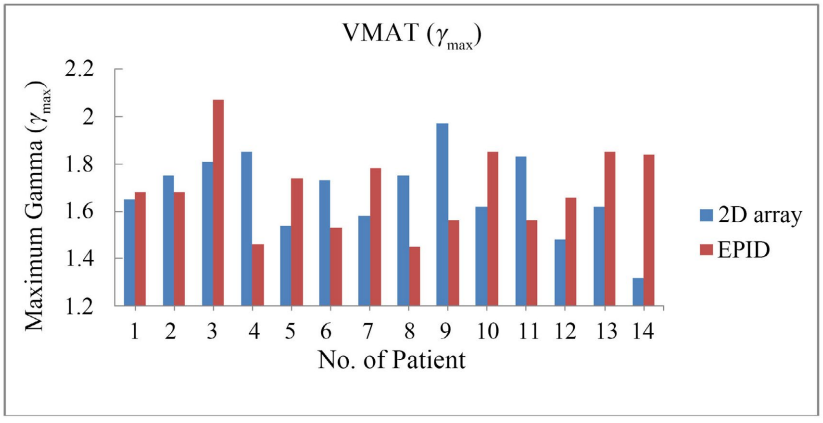


Figure 5. The gamma passed rates of VMAT obtained by comparison of 2D array and EPID results by TPS calculated and measured with different gamma criteria for the maximum gamma (γ_{max}).

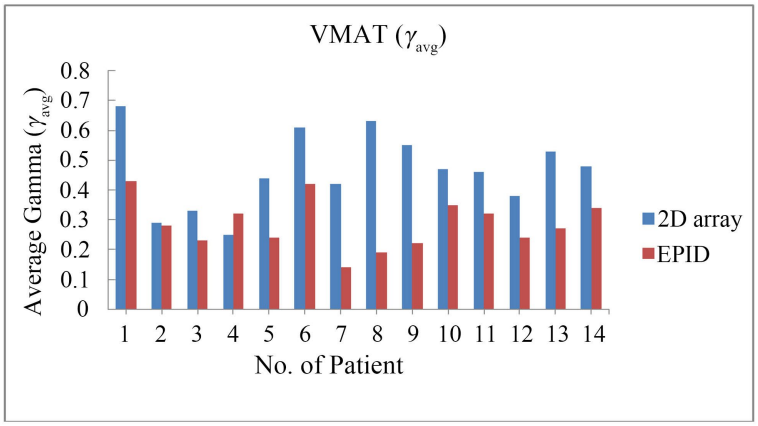


Figure 6. The gamma passed rates of VMAT obtained by comparison of 2D array and EPID results by TPS calculated and measured with different gamma criteria for average gamma (γ_{avg}).

All the IMRT/VMAT plans calculated and measured dose distributions agreed very well, according to the results. The estimated average passing rates of area gamma ($\gamma_{\%\leq 1}$) for the 2D array systems and portal dosimetry (EPID) for 102 IMRT fields were 98.76% and 99.24%, respectively, with standard deviations of 0.61 and 0.37. In VMAT, the average values of portal dosimetry (EPID) and 2D array detectors were 99.00 and 98.91, respectively, with standard deviations of 0.38 and 0.43 are observed in **Table 2** and **Table 3**. For clinical IMRT/VMAT cases, the 2D array detector and portal dosimetry (EPID) systems produce comparable passing rates.

Table 2. Mean and standard deviation of gamma parameters for14 cases 102 IMRT fields estimated using the 2D array and portal dosimetry (EPID).

Cases No.	No. of field	2D array detector			Portal dosimetry		
		$\gamma_{\%\leq 1}$	γ_{max}	γ_{avg}	$\gamma_{\%\leq 1}$	γ_{max}	γ_{avg}
1	7	99.57	1.57	0.26	99.76	1.95	0.23
2	7	98.56	1.78	0.28	99.23	1.87	0.25
3	8	97.82	1.95	0.29	98.72	1.69	0.29
4	7	98.26	2.04	0.27	98.62	1.57	0.19
5	7	98.78	1.57	0.31	99.47	1.35	0.28
6	7	99.15	1.96	0.24	99.45	1.84	0.26
7	7	99.24	1.87	0.25	99.28	1.57	0.24
8	7	98.02	1.48	0.27	98.89	1.68	0.22
9	8	99.04	1.69	0.31	99.38	1.99	0.23
10	8	99.46	1.87	0.3	99.74	1.78	0.3
11	7	99.31	1.58	0.29	99.68	1.32	0.21
12	7	98.18	1.78	0.25	99.09	1.64	0.25
13	8	97.98	2.12	0.23	98.84	1.52	0.22
14	7	99.24	1.33	0.28	99.2	1.58	0.23
Mean		**98.76**	**1.76**	**0.27**	**99.24**	**1.67**	**0.24**
SD		**0.61**	**0.23**	**0.03**	**0.37**	**0.20**	**0.03**

Table 3. Mean and standard deviation of gamma parameters for 14 cases 26 arc fields estimated using the 2D array system and the portal dosimetry (EPID).

Cases No.	No. of arcs	2D array detector			Portal dosimetry		
		$\gamma_{\% \le 1}$	γ_{max}	γ_{avg}	$\gamma_{\% \le 1}$	γ_{max}	γ_{avg}
1	2	98.54	1.65	0.68	98.87	1.68	0.43
2	2	98.75	1.75	0.29	98.89	1.68	0.28
3	2	99.15	1.81	0.33	99.32	2.07	0.23
4	1	98.68	1.85	0.25	98.85	1.46	0.32
5	2	99.24	1.54	0.44	99.52	1.74	0.24
6	2	99.19	1.73	0.61	98.68	1.53	0.42
7	2	99.54	1.58	0.42	99.34	1.78	0.14
8	1	99.32	1.75	0.63	99.25	1.45	0.19
9	2	98.87	1.97	0.55	98.34	1.56	0.22
10	2	98.11	1.62	0.47	98.68	1.85	0.35
11	2	99.15	1.83	0.46	99.45	1.56	0.32
12	2	98.14	1.48	0.38	98.68	1.66	0.24
13	2	99.23	1.62	0.53	99.46	1.85	0.27
14	2	98.79	1.32	0.48	98.67	1.84	0.34
Mean		**98.91**	**1.68**	**0.47**	**99.00**	**1.69**	**0.29**
SD		**0.43**	**0.17**	**0.13**	**0.38**	**0.18**	**0.08**

Recently, portal dosimetry (EPID) was used to validate IMRT or VMAT pretreatment because of the setup efficiency and fast workflow. The calculated and measured dose distributions for all IMRT/VMAT fields are consistent with $\gamma_{\% \le 1}$, $\gamma_{avg < 0.5}$, and γ_{max} values for EPID and 2D array detectors. Our findings agree with the data that has been published [32], the study found significant agreement between calculated and measured dose distributions in all plans, with mean ± SD gamma values: $\gamma_{\% \le 1}$ = 99.43% ± 0.68%, γ_{avg} = 0.24 ± 0.04 and γ_{max} = 2.02 ± 0.66, respectively. 14 patients in the research were estimated using 2D MatriXX detector readings and portal dosimetry. The EPID and 2D array used in patient QA measurement is a good agreement with Jayesh K. *et al.*, who evaluated that the systems of EPID and 2D array detector can be employed in patient-specific QA measures for IMRT and VMAT [33].

3.2. Process Capability Index

For the IMRT and VMAT plans, the X-chart's upper control limit (*UCL*), centerline (*CL*), and lower control limit (*LCL*) were determined. The limitations of X-charts were calculated from 25 cases (177 fields) of IMRT plans; a systematic error for the number of points was identified. As a result, these two points were removed, and new constraints were recalculated. For 25 VMAT plans (43 fields), the data point was not a systematic error, as in these cases a relatively tiny field

size with a complex plan was shown in Figure 7. The IMRT quality's *UCL*, *CL*, and *LCL* values assurance with systematic errors were 100.757%, 99.416%, and 98.075%, respectively. After the systematic errors were removed, the data of *UCL*, *CL*, and *LCL* values were 100.571%, 99.543, and 98.516 respectively. The limitations of the control chart (*UCL*, *CL*, and *LCL*) of VMAT quality assurance QA were 100.697%, 99.180%, and 97.663%, respectively. The maximum gamma evaluation value was 100%; hence, the *UCL* should not be considered. The *LCL* was the only parameter used to define the % gamma pass criteria condition. The mean and standard deviation of all IMRT and VMAT plans with systematic errors are used to evaluate the plan; the average of percentage gamma pass ($\gamma_{\% \le 1}$) was 98.07 ± 0.75% for IMRT QA and 99.06 ± 0.63% for VMAT QA. This meant that the VMAT technique's measured dose distribution was closer to the calculated dose from the Eclipse treatment planning system (TPS) than the IMRT study. Capability index C_{pml} values of 1.36 for IMRT and 1.47 for VMAT validated the outcome. These C_{pml} values are based on results that have been corrected for systematic errors. The capability index (C_{pml}) values were higher than 1.33, indicating that the IMRT and VMAT quality assurance procedures were of high quality.

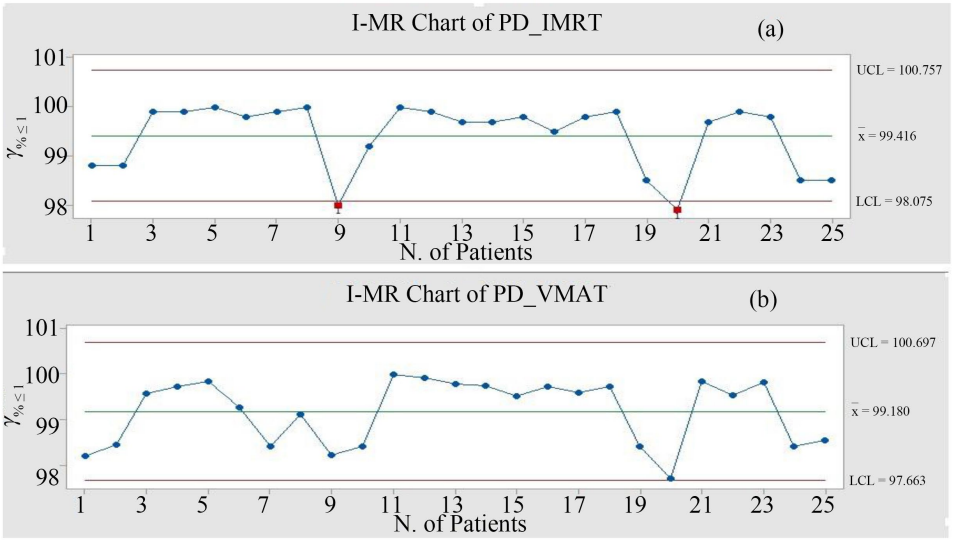


Figure 7. The control chart of % gamma pass (a) IMRT QA and (b) VMAT QA for 25 patients with upper control limit (UCL), centerline (CL) and lower control limit (LCL) with two-point systematic error points of IMRT.

In the context of the control chart analysis, the study differentiated between random variation and systematic error based on the behaviour and origin of the data points. Random variations were attributed to inherent fluctuations in plan complexity such as small-field VMAT arcs or highly modulated beam segments that can naturally influence gamma passing rates without indicating a machine or calibration issue. These points typically remained within control limits or occurred occasionally without a consistent trend. In contrast, a systematic error was identified when data points repeatedly exceeded control limits or showed a con-

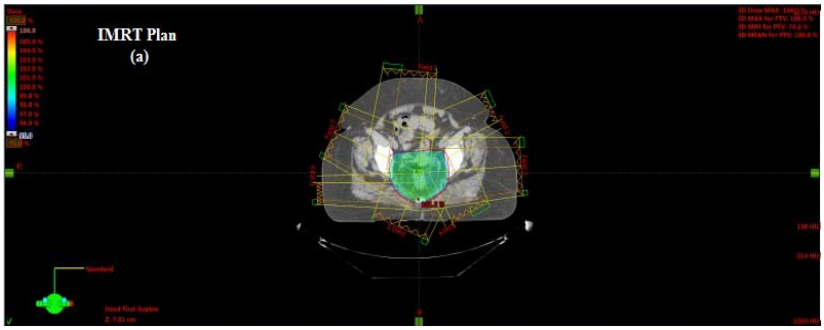
sistent deviation pattern traceable to a specific cause, such as equipment malfunction, calibration drift, or setup error. Only when a deviation met these criteria was it classified as a systematic error and excluded from further analysis to maintain the validity of the control chart.

In this study, the target value $T = 0\%$ used in the process capability index (C_{pml}) calculation does not represent the gamma passing rate itself, but rather the deviation from the target or specification limit. In statistical process control, the C_{pml} equation evaluates how closely the process performance aligns with its specified target. For radiotherapy QA, the gamma pass rate ideally approaches 100%, so the target deviation from 100% becomes zero meaning no difference between measured and calculated dose distributions. Therefore, by setting $T = 0\%$, the analysis treats zero deviation (perfect agreement) as the target condition rather than interpreting it as a literal 0% pass rate.

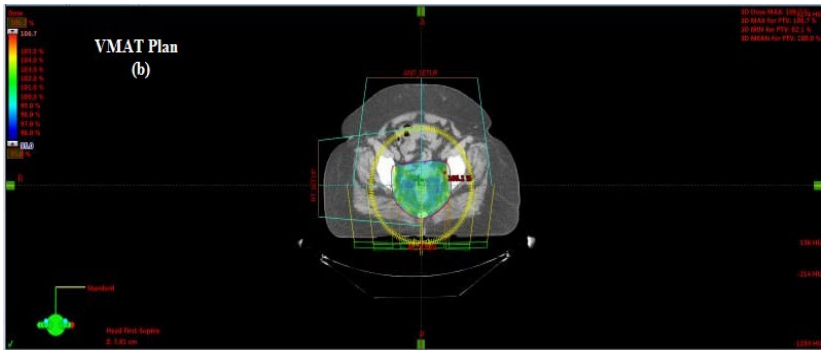
In practical terms, this means that the C_{pml} computation measures how much the observed gamma pass rates deviate from the ideal (100%) within the defined lower control limit (LCL). Thus, $T = 0\%$ refers to zero deviation from the ideal gamma agreement, ensuring the capability index reflects process precision relative to the optimal QA performance standard.

3.3. Comparison of IMRT and VMAT Plans for Rectal Cancer

According to the most recent clinical standards, the dose distribution of the IMRT and VMAT plans for rectal cancer cases was clinically accepted. As seen in **Figure 8**, the medical physicist planned the IMRT and VMAT procedures, and the oncologist chose the best IMRT or VMAT treatment plan for the patient based on the dose volume histogram and isodose evaluation. Conformal isodoses, which are produced by methods like IMRT and VMAT, greatly lower OAR doses and normal tissue toxicity. There have been dosimetric studies that compare IMRT and VMAT with treatment planning system algorithms. For the treatment of rectal cancer, the IMRT plans included seven fields at gantry angles (5˚, 63˚, 86˚, 152˚, 203˚, 269˚, and 294˚). The VMAT plans included two arc beams at various gantry angles from 181˚ to 179˚ clockwise (CW), and another field from 179˚ to 181˚ counterclockwise (CCW). VMAT is an advanced technique, providing efficient and accurate irradiation to planning target volume (PTV) with a linear accelerator (linac) rotating a perfect 360˚ arc.



(a)



(b)

Figure 8. Representative axial computed tomography (CT) images illustrate the configuration of fields for (a) seven-field intensity-modulated radiotherapy (IMRT) and (b) volumetric modulated arc therapy (VMAT). The circular field indicates continuous 360˚ arc of delivery, each intersecting line indicating angle of optimization. Planning target volume (PTV) indicated in green.

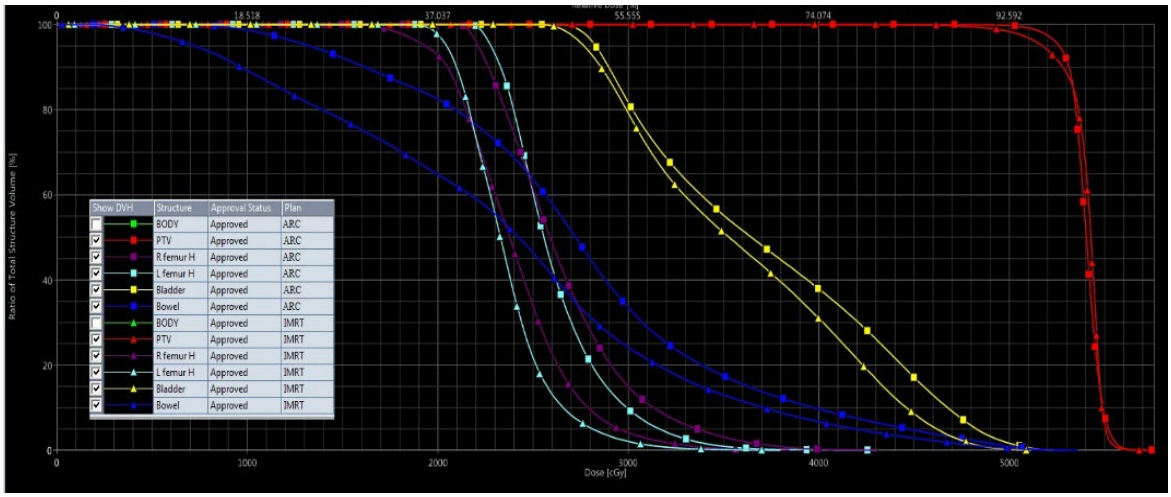


Figure 9. Comparison of dose-volume histogram (DVH) for the IMRT and VMAT rectum plan of PTV and normal tissues using energy 6 MV photon beam.

The comparison between IMRT and VMAT plans found that the dose volume histogram (DVH) of PTV and normal tissues using 6 MV photon beam energy, as shown in **Figure 9**. The dose cover (%) for PTV by IMRT and VMAT equals 100% and the prescribed dose for IMRT or VMAT equals 5400 cGy. The effective treatment delivery time was lowered by almost 50% with VMAT, and the quality of VMAT plans with dual arcs was superior to IMRT plans with five to nine beams. The average percentage of ($\gamma_{\%\leq 1}$) according to 3% dose 3mm distance requirements for IMRT plans was 98.89 ± 0.95, whereas VMAT plans were 99.08 ± 0.82. This study indicates that VMAT is a more effective treatment technique for rectal cancer than IMRT. VMAT had the extra benefit of requiring fewer MUs for treatment than 7-field IMRT. The doses to normal tissues surrounding the planning target volume may have been reduced by higher energy plans in IMRT and VMAT. As a result, employing VMAT with lower energy is preferable than using

IMRT with higher energy. To determine whether better dose distribution using VMAT leads to less toxicity, more research is required, and long-term follow-up is required to evaluate whether VMAT has the potential to reduce the rate of secondary malignancies when compared to IMRT.

4. Conclusions

This work demonstrates strong agreement between calculated and measured dose distributions using a gamma index with 3%/3 mm criteria, highlighting the effectiveness of patient-specific quality assurance (QA) for IMRT and VMAT programs. Both EPID and 2D array detectors exhibited high gamma passing rates, with mean values of 99.24% and 98.76% for IMRT and 99.00% and 98.91% for VMAT, respectively for head and neck cases, confirming their reliability for clinical QA. The utilization of statistical process control (SPC) tools, including control charts and the process capability index (C_{pml}), further validated the stability and efficiency of the QA process, with C_{pml} values of 1.36 for IMRT and 1.47 for VMAT indicating optimal performance. Comparative analysis revealed VMAT's advantages over IMRT, including reduced treatment time and monitor units while maintaining comparable dose conformity for rectal cancer cases. The capability index assessment highlighted areas for improvement in the department's QA infrastructure, particularly QA, to support advanced techniques. Future efforts will focus on refining QA protocols and leveraging big data to enhance radiotherapy QA practices, ultimately improving treatment precision and patient outcomes.

In future work, leveraging big data analytics could enable the development of machine learning based predictive models that use plan complexity metrics such as modulation index, monitor units, or segment shape variability to forecast QA outcomes. By identifying patterns associated with lower gamma pass rates, these models could proactively flag high-risk treatment plans before delivery, allowing physicists to optimize planning parameters or perform targeted QA, ultimately improving treatment safety and efficiency.

5. Long Term Capability Index

To evaluate the current capabilities in our department, the following survey has been established for Capability index scoring. The results above show a significant clinical acceptable accuracy for the quality control and quality assurance programs either for patient specific QA or for the equipment as shown in a previous work. Maintaining this level of quality requires a minimum level of infrastructure in a particular department, this includes equipment, staff level, staff training and up-skills. To evaluate the current capabilities in our department and to what extent that department is able to maintain this level of accuracy, the department has to have a minimum score, the following survey, as shown in Table 4 and Table 5 have been established for this long-term consistency of the Capability index. A minimum score of 20 is introduced as a minimum score to maintain that level of quality, while the maximum score is 40 points.

Table 4. Suggested assessment checklist for IMRT & VMAT dose verification capability.

Section 1: QA Hardware Availability		
What QA tools are available in your department? (*Select all that apply*)	☒ Ion chamber-based phantom ☒ 2D diode/ion chamber array (e.g., MapCHECK) ☒ 3D QA system (e.g., Delta4, ArcCheck) ☐ Film dosimetry ☒ Electronic portal imaging device (EPID) for QA	Scoring: 1 point per item, max 5 points
Section 2: Software Tools		
Which dose verification software features are regularly used? *(Select all that apply)*	☒ Gamma index (2D or 3D analysis) ☐ DVH-based plan QA ☐ Log file-based QA (e.g., Dynalog/TrajectoryLog) ☐ Monte Carlo or advanced dose engine comparison ☐ AI-based QA or error prediction	Scoring: 1 point per item, max 5
Section 3: Verification Coverage		
For which plans is patient-specific QA performed?	☒ All IMRT/VMAT plans ☐ Only complex or high-risk plans ☐ Random audits ☐ Only when issues are suspected	(5 pts) (3 pts) (2 pts) (1 pt)
Section 4: Automation Integration		
To what extent is your QA workflow automated?	☐ Fully automated with scripts and reporting tools ☐ Partially automated ☐ Mostly manual ☐ No automation used (0 pts)	(5 pts) (3 pts) (1 pt) (0 pts)
Section 5: Staff Training & Expertise		
How many staff members are trained in IMRT/VMAT QA protocols?	☐ 5+ ☐ 3 - 4 ☒ 1 - 2 ☐ None	(5 pts) (3 pts) (2 pts) (0 pts)
Section 6: Dose Calculation Verification		
Which secondary dose verification methods are in use? (Select all that apply)	☐ Independent monitor unit check (hand calc or software) ☐ Second dose engine calculation (e.g., AAA vs Acuros) or (Monte Carlo vs Collapsed cone) ☐ Monte Carlo validation ☐ Log file-based dose reconstruction ☒ Third-party verification service or tool	Scoring: 1 point per method, max 5
Section 7: Imaging & Motion QA		
What motion/imaging QA methods are routinely used? (Select all that apply)	☐ MLC log review ☒ Image guidance verification QA ☐ 4D QA for motion (e.g., 4D film/phantoms) ☒ CBCT/IGRT alignment QA ☐ Respiratory gating QA	Scoring: 1 point per item, max 5
Section 8: Continuous Improvement		
How frequently are QA protocols reviewed and updated?	☐ Every 6 months ☐ Annually ☒ Occasionally ☐ Rarely/never	(5 pts) (3 pts) (1 pt) (0 pts)

Table 5. Survey score calculation.

Total Score Calculation:		
Score Range	Capability Level	Current Department Setup score
35 - 40	Leading-edge verification system	
28 - 34	Strong and compliant	
20 - 27	Adequate, with room for optimization	
<20	Needs strategic investment in QA systems	16
	(Max = 40 points)	

The above form helps departments to evaluate their current practice performance and points of weakness. It gives a clear view of the overall process and staff requirements. Although our current IMRT/VMAT verification capability index is higher than 1, the departmental index is lower than 20, that means that this IMRT/VMAT verification can't be maintained for long using the same equipment/staff level. One of the ongoing projects in the department is the Lung SABR, or (Stereotactic Ablative Body Radiotherapy, is a highly focused type of radiation therapy used to treat lung tumors, including both primary lung cancers and secondary (metastatic) tumors that have spread to the lung) [34].

The introduction of this technique will require 4D motion quality assurance and verification. The Thorax dynamic phantom is an example of the required phantom. The use of this phantom will add one more point to the capability score to become 17 points. Furthermore, we will consider reviewing QA protocols annually to increase our capability index to 20 points. That gives us a better position regarding the capability level and gives us more room for further improvements and optimizations for our QA clinical workflow. The use of capability index measures helps us identify our weaknesses and recognize improvement approaches.

Future work includes distributing a further detailed capability index calculation form to relative professional communities and societies to collect more information. Big data analysis could play a crucial role in giving valuable insight into the improvement and upgrade plans for radiotherapy departments.

Conflicts of Interest

The authors confirm that they have no competing interests.

References

[1] Bucci, M.K., Bevan, A. and Roach, M. (2005) Advances in Radiation Therapy: Conventional to 3D, to IMRT, to 4D, and beyond. *CA*: *A Cancer Journal for Clinicians*, **55**, 117-134. https://doi.org/10.3322/canjclin.55.2.117

[2] Konstantinou, E., Varveris, A., Solomou, G., Antoniadis, C., Tolia, M. and Mazonakis, M. (2024) Radiation Dose to Critical Cardiac Structures from Three-Dimensional Conformal Radiation Therapy (3D-CRT), Intensity-Modulated Radiation Therapy (IMRT) and Volumetric Modulated Arc Therapy (VMAT) Techniques for Left-Sided

Breast Cancer. *Journal of Personalized Medicine*, **14**, Article 63. https://doi.org/10.3390/jpm14010063

[3] Alvarez-Moret, J., Pohl, F., Koelbl, O. and Dobler, B. (2010) Evaluation of Volumetric Modulated Arc Therapy (VMAT) with Oncentra Masterplan® for the Treatment of Head and Neck Cancer. *Radiation Oncology*, **5**, Article No. 110. https://doi.org/10.1186/1748-717x-5-110

[4] Bailey, D.W., Kumaraswamy, L., Bakhtiari, M., Malhotra, H.K. and Podgorsak, M.B. (2012) EPID Dosimetry for Pretreatment Quality Assurance with Two Commercial Systems. *Journal of Applied Clinical Medical Physics*, **13**, 82-99. https://doi.org/10.1120/jacmp.v13i4.3736

[5] Onal, C., Arslan, G., Parlak, C. and Sonmez, S. (2014) Comparison of IMRT and VMAT Plans with Different Energy Levels Using Monte-Carlo Algorithm for Prostate Cancer. *Japanese Journal of Radiology*, **32**, 224-232. https://doi.org/10.1007/s11604-014-0291-3

[6] Palta, J.R., Liu, C. and Li, J.G. (2008) Quality Assurance of Intensity-Modulated Radiation Therapy. *International Journal of Radiation Oncology*, *Biology*, *Physics*, **71**, S108-S112. https://doi.org/10.1016/j.ijrobp.2007.05.092

[7] Klein, E.E., Hanley, J., Bayouth, J., Yin, F., Simon, W., Dresser, S., *et al.* (2009) Task Group 142 Report: Quality Assurance of Medical Acceleratorsa). *Medical Physics*, **36**, 4197-4212. https://doi.org/10.1118/1.3190392

[8] Saminathan, S., Manickan, R., Chandraraj, V. and Supe, S.S. (2010) Dosimetric Study of 2D Ion Chamber Array Matrix for the Modern Radiotherapy Treatment Verification. *Journal of Applied Clinical Medical Physics*, **11**, 116-127. https://doi.org/10.1120/jacmp.v11i2.3076

[9] Low, D.A., Harms, W.B., Mutic, S. and Purdy, J.A. (1998) A Technique for the Quantitative Evaluation of Dose Distributions. *Medical Physics*, **25**, 656-661. https://doi.org/10.1118/1.598248

[10] Mohamed, I.E., Ibrahim, A.G., Zidan, H.M., El-Bahkiry, H.S. and El-sahragti, A.Y. (2018) Physical Dosimetry of Volumetric Modulated Arc Therapy (VMAT) Using EPID and 2D Array for Quality Assurance. *The Egyptian Journal of Radiology and Nuclear Medicine*, **49**, 477-484. https://doi.org/10.1016/j.ejrnm.2018.02.003

[11] Pawlicki, T., Whitaker, M. and Boyer, A.L. (2005) Statistical Process Control for Radiotherapy Quality Assurance. *Medical Physics*, **32**, 2777-2786. https://doi.org/10.1118/1.2001209

[12] Nordström, F., Af Wetterstedt, S., Johnsson, S., Ceberg, C. and Bäck, S.Å.J. (2012) Control Chart Analysis of Data from a Multicenter Monitor Unit Verification Study. *Radiotherapy and Oncology*, **102**, 364-370. https://doi.org/10.1016/j.radonc.2011.11.016

[13] Rajasekaran, D., Jeevanandam, P., Sukumar, P., Ranganathan, A., Johnjothi, S. and Nagarajan, V. (2015) A Study on the Correlation between Plan Complexity and Gamma Index Analysis in Patient Specific Quality Assurance of Volumetric Modulated Arc Therapy. *Reports of Practical Oncology & Radiotherapy*, **20**, 57-65. https://doi.org/10.1016/j.rpor.2014.08.006

[14] Roy, A., Cutright, D., Gopalakrishnan, M., Yeh, A.B. and Mittal, B.B. (2020) A Risk-Adjusted Control Chart to Evaluate Intensity Modulated Radiation Therapy Plan Quality. *Advances in Radiation Oncology*, **5**, 1032-1041. https://doi.org/10.1016/j.adro.2019.11.006

[15] Pawlicki, T., Yoo, S., Court, L.E., McMillan, S.K., Rice, R.K., Russell, J.D., *et al.* (2008) Moving from IMRT QA Measurements toward Independent Computer Calculations

Using Control Charts. *Radiotherapy and Oncology*, **89**, 330-337. https://doi.org/10.1016/j.radonc.2008.07.002

[16] Sanghangthum, T., Suriyapee, S., Srisatit, S. and Pawlicki, T. (2013) Statistical Process Control Analysis for Patient-Specific IMRT and VMAT QA. *Journal of Radiation Research*, **54**, 546-552. https://doi.org/10.1093/jrr/rrs112

[17] Raveendran, V., Anjana, P.T., Bhasi, S., Ranjith, C.P. and Kinhikar, R.A. (2023) Moving towards Process-Based Radiotherapy Quality Assurance Using Statistical Process Control. *Physica Medica*, **112**, Article 102651. https://doi.org/10.1016/j.ejmp.2023.102651

[18] Jacob, P. (2024) Comparison of Arccheck and Portal Dosimetry in Dose Verification for Intensity Modulated Radiotherapy (IMRT) and Rapidarc Plans. *Journal of Oncology Research Reviews & Reports*, **5**, 1-5. https://doi.org/10.47363/jonrr/2024(5)179

[19] Webster, M., Podgorsak, A., Li, F., Zhou, Y., Jung, H., Yoon, J., *et al.* (2025) New Approaches in Radiotherapy. *Cancers*, **17**, Article No. 1980. https://doi.org/10.3390/cancers17121980

[20] Das, S., Kharade, V., Pandey, V., KV, A., Pasricha, R.K. and Gupta, M. (2022) Gamma Index Analysis as a Patient-Specific Quality Assurance Tool for High-Precision Radiotherapy: A Clinical Perspective of Single Institute Experience. *Cureus*, **14**, e30885. https://doi.org/10.7759/cureus.30885

[21] Depuydt, T., Van Esch, A. and Huyskens, D.P. (2002) A Quantitative Evaluation of IMRT Dose Distributions: Refinement and Clinical Assessment of the Gamma Evaluation. *Radiotherapy and Oncology*, **62**, 309-319.

[22] Spezi, E. and Lewis, D.G. (2006) Gamma Histograms for Radiotherapy Plan Evaluation. *Radiotherapy and Oncology*, **79**, 224-230. https://doi.org/10.1016/j.radonc.2006.03.020

[23] Miften, M., Olch, A., Mihailidis, D., Moran, J., Pawlicki, T., Molineu, A., *et al.* (2018) Tolerance Limits and Methodologies for IMRT Measurement-Based Verification QA: Recommendations of AAPM Task Group No. 218. *Medical Physics*, **45**, e53-e83. https://doi.org/10.1002/mp.12810

[24] Agazaryan, N., Solberg, T.D. and DeMarco, J.J. (2003) Patient Specific Quality Assurance for the Delivery of Intensity Modulated Radiotherapy. *Journal of Applied Clinical Medical Physics*, **4**, 40-50. https://doi.org/10.1120/jacmp.v4i1.2540

[25] Ryan, T.P. (2006) Mastering Statistical Process Control: A Handbook for Performance Improvement Using Cases. *Journal of Quality Technology*, **38**, 294-296.

[26] Pawlicki, T., Chera, B., Ning, T. and Marks, L.B. (2012) The Systematic Application of Quality Measures and Process Control in Clinical Radiation Oncology. *Seminars in Radiation Oncology*, **22**, 70-76. https://doi.org/10.1016/j.semradonc.2011.09.006

[27] Chan, L.K., Cheng, S.W. and Spiring, F.A. (1988) A New Measure of Process Capability: C pm. *Journal of Quality Technology*, **20**, 162-175. https://doi.org/10.1080/00224065.1988.11979102

[28] Chaikh, A. and Balosso, J. (2016) Statistical Control Process to Compare and Rank Treatment Plans in Radiation Oncology: Impact of Heterogeneity Correction on Treatment Planning in Lung Cancer. *Translational Lung Cancer Research*, **5**, 688-694. https://doi.org/10.21037/tlcr.2016.09.04

[29] Wheeler, D.J. and Chambers, D.S. (1992) Understanding Statistical Process Control. 3rd Edition, SPC Press.

[30] Pillet, M., Rochon, S. and Duclos, E. (1997) SPC—Generalization of Capability Index

C pm: Case of Unilateral Tolerances. *Quality Engineering*, **10**, 171-1766.

[31] Fuangrod, T., Greer, P.B., Woodruff, H.C., Simpson, J., Bhatia, S., Zwan, B., *et al.* (2016) Investigation of a Real-Time EPID-Based Patient Dose Monitoring Safety System Using Site-Specific Control Limits. *Radiation Oncology*, **11**, Article No. 106. https://doi.org/10.1186/s13014-016-0682-y

[32] Sharma, D.S., Mhatre, V., Heigrujam, M., Talapatra, K. and Mallik, S. (2010) Portal Dosimetry for Pretreatment Verification of IMRT Plan: A Comparison with 2D Ion Chamber Array. *Journal of Applied Clinical Medical Physics*, **11**, 238-248. https://doi.org/10.1120/jacmp.v11i4.3268

[33] Jayesh, K., Ganesh, T., Suganthi, D., Mohan, R., Rakesh, C.J., Sarojkumar, D.M. and Jacob, S.J. (2013) Dosimetric Comparison of aSi1000 EPID and ImatriXX 2-D Array System for Volumetric Modulated Arc and Intensity Modulated Radiotherapy Patient Specific Quality Assurance, World Academy of Science, Engineering and Technology. *International Journal of Physical and Mathematical Sciences*, **7**.

[34] Goldsmith, C. and Gaya, A. (2012) Stereotactic Ablative Body Radiotherapy (SABR) for Primary and Secondary Lung Tumours. *Cancer Imaging*, **12**, 351-360. https://doi.org/10.1102/1470-7330.2012.9015

Abbreviations

IMRT	Intensity-modulated radiotherapy
VMAT	Volumetric modulated arc therapy
SPC	Statistical Process Control
C_{pml}	capability index
QA	Quality Assurance
Linac	linear accelerator
TPS	treatment planning system
aSi-1000 EPID	amorphous silicon electronic portal imaging device
Exact-Arm	robotic support arm
CU	calibration units
MUs	monitor units
6MV	6 megavoltage
cGy	centigray
PTV	planning target volume
OAR	organ-at-risk
2D-RT	two-dimensional radiotherapy
3D-CRT	three-dimensional conformal radiotherapy
MLC	multi-leaf collimator
(γ)	gamma index
(γ_{max})	maximum gamma index
(γ_{avg})	average gamma index
DTA	distance-to-agreement
DD	dose difference
AAPM TG114	American Association of Physicists in Medicine Task Group 114
DVH	Dose Volume Histogram
CW	clockwise
CCW	counterclockwise
AAA	Algorithm of Anisotropic Analysis
UCL	Upper Control Limit
CL	centerline
LCL	Lower Control Limit
$\overline{x}$	average of percentage gamma pass
(σ)	Standard Deviation of % gamma pass
$\overline{mR}$	average percentage of gamma pass
7-fields IMRT	seven-field intensity-modulated radiotherapy (IMRT)