REPORTS OF PRACTICAL ONCOLOGY AND RADIOTHERAPY 24 (2019) 124–132

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journal homepage: http://www.elsevier.com/locate/rpor

Original research article

Multi-institutional evaluation using the end-to-end test for implementation of dynamic techniques of radiation therapy in Thailand

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ARTICLE INFO

Article history:
Received 10 July 2018
Received in revised form
23 September 2018
Accepted 10 November 2018
Available online 28 November 2018

Keywords:
IMRT
VMAT

ABSTRACT

Aim: In this study, an accuracy survey of intensity-modulated radiation therapy (IMRT) and volumetric arc radiation therapy (VMAT) implementation in radiotherapy centers in Thailand was conducted.

Background: It is well recognized that there is a need for radiotherapy centers to evaluate the accuracy levels of their current practices, and use the related information to identify opportunities for future development.

Materials and methods: An end-to-end test using a CIRS thorax phantom was carried out at 8 participating centers. Based on each center's protocol for simulation and planning, linac-based IMRT or VMAT plans were generated following the IAEA (CRP E24017) guidelines. Point doses in the region of PTVs and OARs were obtained from 5 ionization chamber readings

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https://doi.org/10.1016/j.rpor.2018.11.005

Quality assurance
Accuracy
End-to-end test

and the dose distribution from the radiochromic films. The global gamma indices of the measurement doses and the treatment planning system calculation doses were compared.
Results: The large majority of the RT centers (6/8) fulfilled the dosimetric goals, with the measured and calculated doses at the specification points agreeing within ±3% for PTV and ±5% for OARS. At 2 centers, TPS underestimated the lung doses by about 6% and spinal cord doses by 8%. The mean percentage gamma pass rates for the 8 centers were 98.29 ± 0.67% (for the 3%/3 mm criterion) and 96.72 ± 0.84% (for the 2%/2 mm criterion).
Conclusions: The 8 participating RT centers achieved a satisfactory quality level of IMRT/VMAT clinical implementation.

1. Background

Intensity-modulated radiotherapy (IMRT) and volumetric modulated arc therapy (VMAT) have demonstrated the ability to deliver radiation doses that conform to convoluted shapes at a variety of tumor sites.[1–6] Given the complexities of these dynamic delivery methods, IMRT and VMAT are acknowledged to be practiced with varying quality at institutions. It is therefore crucial that radiotherapy (RT) departments address their levels of accuracy and the uncertainties related to these advanced technologies, and use the information relating to their current practices to identify opportunities for future development.

Several professional organizations, including the American Association of Physicists in Medicine (AAPM) and the European Society for Therapeutic Radiology and Oncology, have provided comprehensive quality assurance and verification methods for IMRT and VMAT.[7,8] Credentialing programs and guidelines for IMRT in clinical trials have been developed.[9–11] The AAPM Task Group 119 has performed phantom measurements in a multi-institutional study to quantify the confidence limits for IMRT commissioning.[12] Several British groups have performed external audit programs and provided guidelines for the safe delivery of the IMRT process as well as credentials for static and rotational IMRT delivery to ensure clinical trial quality assurance.[13–16] In Asia, researchers in Japan, India, and Korea have also reported on quality surveys of IMRT/VAMAT and their accuracy levels in clinical practice.[17–20] In addition, a number of studies in a range of countries have evaluated multi-institutional IMRT/VMAT accuracy using various methodologies.[21–26] The reports have emphasized the need for high accuracy levels in the use of these complex technologies in radiation oncology.

As to Thailand, the first IMRT was implemented at the Department of Radiation Oncology, Faculty of Medicine, Siriraj Hospital, in the year 2005. According to the 2016–2017 annual survey of the Thai Association of Radiology and Radiotherapeutic Oncology (THASTRO).[27] IMRT/VMAT had been implemented at a total of 22 of the 34 RT facilities in Thailand, and around 6000 cancer patients were treated annually at that time.

In the year 2014, The International Atomic Energy Agency (IAEA) proposed the Coordinated Research Project (CRP) with the following aim: "To Investigate the Relationship Between end to end Accuracy and Quality Assurance Extent and Depth in Radiotherapy" (CRP E24017). The program dealt with the quality assurance aspects of advanced radiation therapy performed at all RT centers at the international level, with the dose-delivery accuracies being assessed by end-to-end tests. In the case of Thailand, 8 RT institutes participated in the program during 2015–2017; those institutions, which comprised academic and private hospitals, handled 3593 IMRT/VMAT patients (60% of all IMRT/VMAT patients in Bangkok).[27] End-to-end tests were performed; they verified the chain in the IMRT/VMAT radiotherapy workflow, from patient-data acquisition to treatment planning and dose delivery.

2. Aim

This work conducted the end-to-end test on a national scale to assess the current status and accuracy of the implementation of dynamic techniques of radiation therapy. Details of the methodology, survey results, and possible sources of errors are reported and discussed.

3. Materials and methods

3.1. *Simulation and treatment planning*

The end-to-end surveys were performed between September 2015 and December 2016 at 4 academic hospitals, 2 cancer centers, and 2 private hospitals. Except for 1 center in northeastern Thailand, the facilities were located in Bangkok. Based on the IAEA CRP E24017 protocol, clinically realistic IMRT/VMAT plans were evaluated on the semi-anthropomorphic phantom CIRS Thorax 002LFC (CIRS Inc., Norfolk, VA, USA). This inhomogeneous phantom represents an average human torso both in terms of proportion and relative electron density (1.003, 1.506, and 0.207 for plastic water, bone, and lungs, respectively).

The phantom was delivered to each participating center to replicate clinical workflows, from simulation, contouring, planning, positioning, and delivery of the treatment plan. Local staff used their routine practices to perform CT imaging of the phantom, and the tomographic images were sent to the treatment planning system (TPS) for organ segmentation. To ensure the reproducibility and standardization of the end-to-end tests, a set of standard DICOM format structures, as shown in Fig. 1, was provided by the IAEA workgroup. Organ

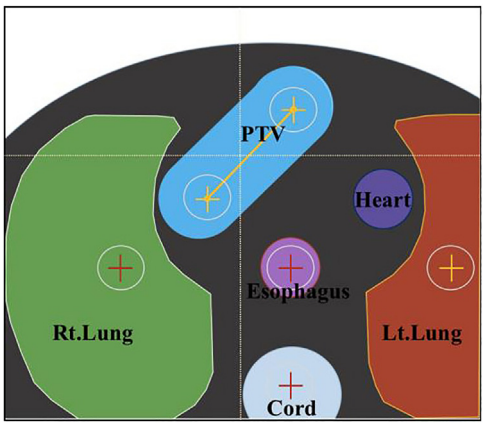

Fig. 1 – The IAEA DICOM structure set contained the planned target volume (PTV), and the organs at risk (OARs), namely, the heart, esophagus, lungs, and spinal cord, to create the IMRT/VMAT plan.

delineation could be either performed using the automatic registration tool in the TPS, or drawn manually in accordance with the supervision guidelines. A contour of the external surface and a ring at 2 mm depth were also included for optimization purposes. To avoid affecting the dose calculation using the VMAT technique, it was suggested that 4 fixation nylon rods on the CIRS phantom also be outlined. Depending on the local clinical practices, the photon energy could be selected between 6–15 MV, with the total prescribed dose to planned target volume (PTV) set at 50.4 Gy in 28 fractions. The goal of the planning, 1.8 Gy at 95% isodose, should cover the planned target volume (PTV) and not be greater than 110% for the hot spot. The IMRT/VMAT plan was optimized to meet all PTV and critical structure dose constraints, as outlined by the protocol (Table 1). The facility characteristics and details of the parameters used in the planning at the participating centers are summarized in Table 2.

3.2. *Dose delivery and phantom measurements*

All institutions in this survey had been participating in the IAEA/WHO TLD postal audit system.[28] A small-volume ion chamber (0.12–0.13 cm^3 cavity volume) and electrometer which had received a calibration certificate from the National Secondary Standards Dosimetry Laboratory (SSDL) were requested for the absolute dose measurements. The workgroup also supplied each center with the Gafchromic EBT3 films for film calibrations and for use with the measurements of the complex IMRT/VMAT dose distributions.

On the day of treatment delivery, the reference beam output was verified in the CIRS phantom at position no. 1, as shown in Fig. 2(a), by using a single field of 6 MV photons, 0° gantry angle, 100 cm SSD, the nominal dose rate, and a 10 × 10 cm field size with 200 MU. The CIRS anthropomorphic phantom was positioned and aligned by the host center using the laser positioning system either alone or in conjunction with the image-guidance system. The phantom was irradiated according to the developed IMRT/VMAT plan. Five absolute dose points (comprising no. 1 and 2 for dose verification in PTV, no. 5 for the esophagus, no. 6 for the lungs, and no. 10 for the spinal cord; Fig. 2(b)) were measured and repeated 3 times.

As to the film dosimetry, film calibration was performed at the individual center using 5 × 5 cm^2 films at a 5 cm depth in a layered water-equivalent phantom and a 10 × 10 cm^2 photon field, with a source-to-film distance of 100 cm. Nine different dose levels, from 10 to 300 cGy, were used to create a sensitometric curve. A full-sized film was placed at the adjacent phantom slice, at Z = 1.5 cm from the phantom center, and parallel to the beam axis, to measure the IMRT/VMAT dose distribution and compared to the TPS calculation as shown in Fig. 3.

At the processing center, a VIDAR DosimetryPRO Advantage (Red) scanner and OmniPro-I'mRT software were used to read the optical density and perform the film analysis. The region of interest for the dose calibration and calculation was selected to avoid the pinprick and marker areas. The dose normalization was set at the beam isocenter for a TPS comparison. Agreement of the 3D dose distribution using a 3D global gamma analysis with the acceptance criteria of 4%/3 mm, 3%/3 mm, 3%/2 mm, and 2%/2 mm, and with a 10% low-dose threshold, was performed and analyzed.

4. Results

4.1. *IMRT/VMAT plan quality*

Table 3 presents the structure volumes and results of the IMRT/VMAT plans from all of the participating institutes. The majority of the centers fulfilled the dosimetric goal, but variable plan quality and organ contours were presented by a few centers. For instance, the maximum point dose and dose to <10 cc of the skin in centers E and F were notably higher than defined by the protocol.

Table 1 – Prescribed OAR dose constraints, using the IAEA (CRP E20417) guidelines.

Structure	Volume (cc)	Max volume dose (cGy)	Max point dose (cGy)
Spinal cord	<1	1550	1700
	<5	1450	
Heart	<15	1800	2350
Esophagus	<5	4400	5050
Skin	<10	1600	2400
Total lungs	500	1650	500

Table 2 – Summary of the facility characteristics and planning parameters used in the end-to-end phantom verifications at the 8 RT centers.

Facility	Institute							
	A	B	C	D	E	F	G	H
CT unit	GE Optima	Phillips Brilliance	Phillips Brilliance	Phillips Brilliance	Toshiba Aquilion	Phillips Brilliance	Phillips Brilliance	Phillips Brilliance
Slice thickness	2.5 mm	3 mm	3 mm	3 mm	3 mm	3 mm	3 mm	3 mm
Machine	Varian	Varian	Varian	Varian	Siemens	Elekta	Varian	Elekta
Model	Clinac iX	Clinac iX	Truebeam	Trilogy	Oncor Compression	Synergy	Clinac iX	Axesse
MLC	120[a]	120	120	120	80[b]	80	120	160[c]
TPS model	Eclipse	Eclipse	Eclipse	Eclipse	Oncentra	Monaco	Eclipse	Monaco
Algorithm	AAA	AAA	AAA	AAA	Collapse cone	Monte Carlo	AAA	Monte Carlo
	13.6.23	10.0.28	11.0.31	10.0.28	4.3	3.00.00	11.0.31	5.00.04
Grid size	2.5 mm	2.5 mm	2.5 mm	2.5 mm	3 mm	3 mm	2.5 mm	3 mm
Delivery technique	RapidArc	RapidArc	RapidArc	Rapid Arc	IMRT	IMRT	Rapid Arc	VMAT
Number of arc	2 full arcs	2 partial arcs	3 partial arcs	2 partial arcs	Step-shoot 9 F	Step-shoot 5 F	2 partial arcs	2 partial arcs
Energy	6 MV	6 MV	6 MV	6 MV	6 MV	6 MV	6 MV	6 MV
Image guidance	–	kV-CBCT	kV-CBCT	kV-CBCT	–	kV-CBCT	–	–

[a] 120 MLC (field size 40 × 40 cm – 5 mm leaf width at inner 20 cm, and 10 mm leaf width at outer 20 cm of field).
[b] 80 MLC (field size 40 × 40 cm, leaf width 10 mm).
[c] 160 agility MLC (field size 40 × 40 cm, leaf width – 5 mm).

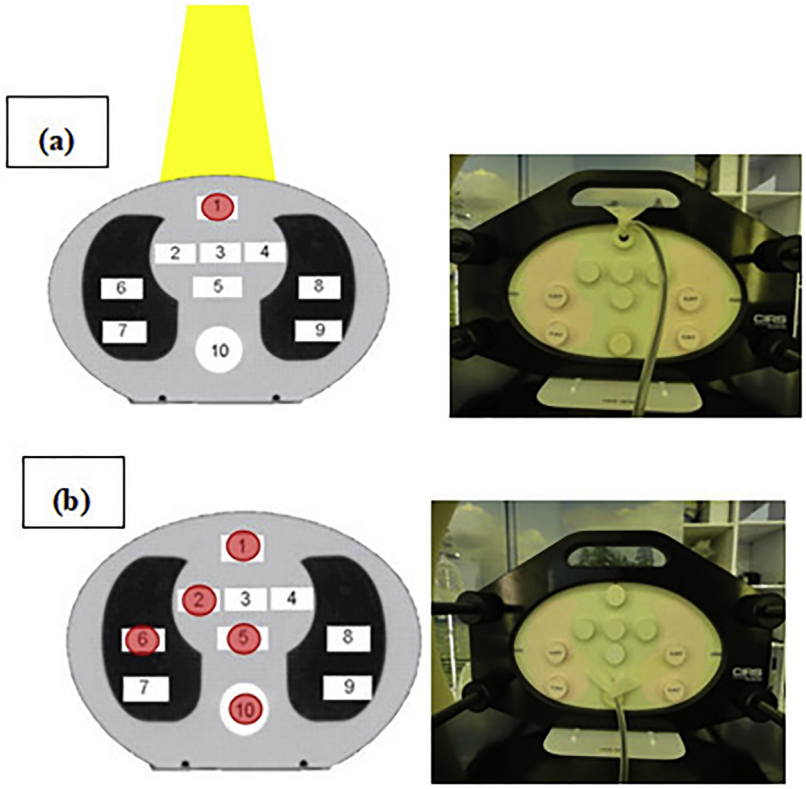

Fig. 2 – (a) The linac output consistency was checked at measuring point no. 1 in the CIRS phantom, which was at a 3 cm depth, and was compared with the TPS reading dose. (b) Using the CC13 ionization chamber, 5 absolute point doses were measured at nos. 1 and 2 for PTV; and nos. 5, 6, and 10 for the esophagus, lungs, and spinal cord, respectively.

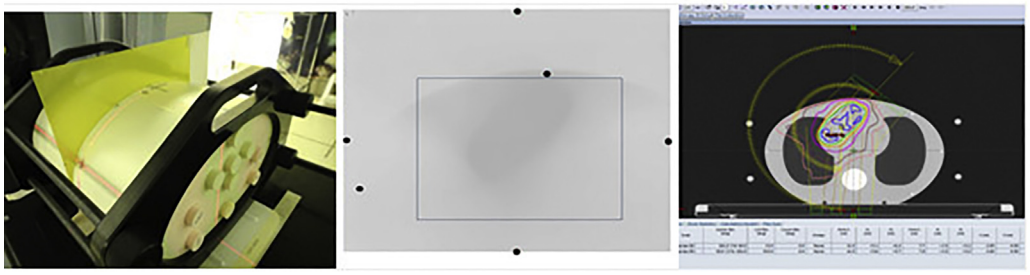

Fig. 3 – A full-sized film was placed at the adjacent phantom slice at Z = 1.5 cm from the phantom center, and parallel to the beam axis, to measure the IMRT/VMAT dose distribution and compared to the TPS calculation.

4.2. *Machine output consistency*

To ensure consistency of the machine performance, the beam outputs on the day of the dose delivery, when compared with the TPS dose at the reference condition at each center, were within ±1.5%, and the mean ± SE of the deviation was minus 0.20 ± 0.38 (Table 4).

4.3. *Measurement of point dose and dose distribution*

The measured doses at the point of interest for each RT center are in Table 5. The mean ± SE of the dose difference between the measurement and the calculation for 2 points in PTV from all centers were minus 0.30 ± 0.47and 0.51 ± 0.51, respectively (−2.75% to 2.86%). As for organs at risk (OARs), most of the centers presented a dose agreement within ±2% for the esophagus, and ±5% for the lungs and the spinal cord. However, underestimated TPS reading doses of about 6% for the lungs and 8% for the spinal cord were found at 2 RT centers.

With regard to the complex IMRT/VMAT dose distribution, the percentages for the gamma pass rate for each gamma criterion are in Table 6. It can be seen that, for all criteria from 4%/3 mm down to 2%/2 mm, the mean gamma pass rate for all departments exceeded 95%. This finding highlights the capability of the machine to accurately control complex treatment parameters as defined by the inverse planning system. The gamma pass rate data grouped by the TPS model are also presented in Table 7; the Monte Carlo algorithm showed a higher pass rate at any criterion than for the other algorithms.

Table 3 – Treatment plan results.

Dose (cGy)	Constraints	A	B	C	D	E	F	G	H
PTV									
Volume (cc)		136.0	125.9	130.4	127.3	99.5	157.9	132.6	131.6
Max point dose	<5544	5393	5540	5420	5539	5401	5442	5530	5442
D95	>5040	5040	5058	5080	5043	5000	5085	5054	5101
Spinal cord									
Volume (cc)		181.1	126.5	129.4	125.8	141.0	144.4	130.9	132.5
Max point dose	1700	1618	1469	1380	1337	492	1446	1669	1397
<1 cc	1550	1500	1314	1260	1198	477	1170	1489	1279
<5 cc	1450	1437	1199	1058	1095	400	1030	1325	1164
Heart									
Volume (cc)		74.4	78.7	82.2	77.8	67.6	79.9	74.9	72.8
Max point dose	2350	2259	1772	2260	1476	1320	1750	2324	1847
<15 cc	1800	1683	1192	1655	965	898	913	1534	1237
Esophagus									
Volume (cc)		48.5	50.5	47.4	50.5	46.0	54.9	51.1	55.4
Max point dose	5050	3575	3205	3598	2995	4086	2584	3632	3033
<5 cc	4400	2969	2419	2924	2281	3750	1870	2913	2491
Skin									
Volume (cc)		1439.9	1446.6	778.4	1199.2	1082.5	458.5	1811.5	1323.6
Max point dose	2400	2248	2857	1895	2338	3872	3695	2537	2914
<10 cc	1600	1009	1003	923	1052	2500	2500	1019	1268
Whole lung									
Volume (cc)		4743.7	5525.4	5226	5506.5	4870.7	5158.4	5062.0	5027.4
Max point dose	5000	4888	4348	4470	4893	4090	4675	4833	4629
500 cc	1650	1190	782	1002	669	622	1026	871	1026

Table 4 – Machine output verification.

Dose (Gy)	A	B	C	D	E	F	G	H	Mean ± SE
Planned dose	1.828	1.899	1.838	1.838	1.82	1.89	1.864	1.878	
Measured dose	1.849	1.895	1.826	1.85	1.847	1.903	1.859	1.853	
% dose difference	−1.136	0.227	−0.151	−0.632	−1.475	−0.692	0.269	1.349	−0.2003 ± 0.38

Table 5 – Percentage dose difference between the planned and measured doses for PTV and OARs (prescription dose = 1.8 Gy/fraction).

Structure (cGy)	A	B	C	D	E	F	G	H	Mean ± SE
PTV point 1									
Planned dose	1.845	1.865	1.850	1.874	1.840	1.857	1.836	1.856	–
Measured dose	1.843	1.872	1.872	1.885	1.841	1.846	1.887	1.827	–
% difference	0.12	−0.38	−1.17	−0.58	−0.05	0.62	−2.75	1.77	−0.30 ± 0.47
PTV point 2									
Expected dose	1.856	1.895	1.837	1.869	1.830	1.875	1.837	1.876	–
Measured dose	1.825	1.842	1.835	1.907	1.812	1.872	1.847	1.861	–
% difference	1.69	2.86	0.12	−1.97	1.00	0.14	−0.56	0.78	0.51 ± 0.51
Esophagus									
Planned dose	1.007	0.729	0.979	0.715	0.220	0.813	0.857	0.816	–
Measured dose	0.991	0.746	0.999	0.711	0.224	0.828	0.873	0.782	–
% difference	1.63	−2.27	−2.08	−0.07	−1.52	−1.84	−1.84	4.34	−0.46 ± 0.83
Right lung									
Planned dose	0.630	0.751	0.390	0.490	1.050	0.907	0.402	0.912	–
Measured dose	0.626	0.721	0.416	0.526	1.054	0.891	0.391	0.869	–
% difference	0.59	4.15	−6.14	−6.68	−0.33	1.72	2.89	5.51	0.21 ± 1.59
Spinal cord									
Planned dose	0.451	0.375	0.351	0.266	0.130	0.408	0.431	0.318	–
Measured dose	0.446	0.386	0.357	0.291	0.130	0.443	0.414	0.321	–
% difference	1.12	−2.95	−1.61	−8.64	−0.21	−7.84	4.07	−0.83	−2.11 ± 1.52

Table 6 – The gamma pass rate for each gamma criterion at all participating RT centers.

Gamma criteria	A	B	C	D	E	F	G	H	Mean ± SE
2%/2 mm	96.8	96.6	96.1	97.3	98	97.8	91.5	99.7	96.72 ± 0.84
3%/2 mm	98.0	98.5	97.0	98.3	98.8	98.9	93.0	99.8	97.79 ± 0.74
3%/3 mm	98.6	99.1	97.8	98.7	99.2	99.3	93.8	99.8	98.29 ± 0.67
4%/3 mm	99.2	99.8	98.5	99.2	99.4	99.8	94.7	99.9	98.81 ± 0.61

Table 7 – The gamma pass rate data for different gamma criteria (threshold = 10%), grouped by TPS model.

TPS model	2%/2 mm	3%/2 mm	3%/3 mm	4%/3 mm
AAA(5 centers)	95.66	96.96	98.28	98.28
CCC (1 center)	98.00	98.80	99.20	99.40
MC (2 centers)	98.75	99.35	99.55	99.85

AAA: analytical anisotropic algorithm; CCC: collapsed cone convolution; MC: Monte Carlo.

5. Discussion

There exist a number of methods for IMRT/VMAT accuracy verification. In this study, we used the end-to-end test to conduct a multi-institutional assessment at multiple sites in Thailand. The presence of detectable errors in the IMRT/VMAT treatment chain, which relate to the heterogeneities typically found in patients in a clinical environment could potentially lead to improved outcomes.

All centers used 6 MV photon beams with a good output agreement. Despite the institutes in the present study showing variations in the levels of technical resources and radiotherapy personnel experience (2–13 years), data relating to the planning and dose to OARs conformed with the protocol (Table 3). In the case of some centers with RT-structure DICOM import problems, the volume of the delineated organs obtained from the manual method showed a degree of variation from the average; however, we found that the deviations did not affect the planning outcomes. Two centers (E and F) recognized the limitations of their old version of TPS in creating a surface contour and ring for optimization, resulting in a higher skin dose in their IMRT/VMAT plans.

The overall results showed excellent agreement of the measured and planned doses, and they were in line with other multi-institutional IMRT/VMAT audits.[16,22,24–26,29] In our survey, the acceptable levels of dose discrepancies at the specification points of ±3% for PTV and ±5% for OARS were achieved by the large majority of the 8 centers. However, the TPS dose for the lungs was underestimated by about 6% at 2 centers (C and D); both institutions used RapidArc/Varian/AAA. Moreover, the TPS dose for the spinal cord was underestimated by 8% at centers D and F; in those cases, although one institution used RapidArc/Varian/AAA, the other used step-and-shoot/Elekta/MC. Unfortunately, due to the limited data, it was not possible to find a correlation between the dose deviation and the technique, type of treatment machine, or TPS model. Factors related to dose uncertainty can be related to the CT-number to electron-density conversion, the setup accuracy, and whether the measuring point is located in a low-dose or high-gradient region. There has been a report that end-to-end tests with anthropomorphic phantoms which yielded a 5% uncertainty in dose delivery were likely to provide underestimates in real-patient treatments.[30] This highlights the need for RT centers to be aware of their accuracy levels and uncertainty issues in order to provide full benefits to patients.

Of the 8 participating machines (5 Varian-Rapid Arc plans, 2 Elekta-IMRT and VMAT, and 1 Siemens-IMRT), all presented an excellent average pass rate of 97–99%, from criteria of 2%/2 mm to 4%/3 mm. However, it was noticeable that 1 center had lower gamma pass rates (93.8% with 3%/3 mm, and 91.5% with 2%/2 mm) than the other centers using the same Varian-Rapid Arc technique. The accuracy of Varian plans has been reported in a study by Servavalli et al.[26] They used predefined treatment plans to audit local methods to assess quality assurance in radiotherapy, and the average pass rates obtained from the array audits of all of the Varian plans were 97.8% (3%/3 mm) and 96.2% (3%/2 mm), which were similar to our Varian results. The treatment workflow was reviewed, and the planning isocenter for this VMAT plan was found to be located 2 cm laterally and 4 cm inferior to the center of PTV. The off-center technique was also studied by Calvo-Ortega et al.[31] They proposed the use of a technique involving the placement of the isocenter at a patient's midline during breast radiation treatment in order to avoid the risk of collisions during the image-guided setup and treatment delivery. A comparable planning dosimetric outcome with the reference technique was obtained, but the study did not report on the dose delivery accuracy. From the dosimetric and physics standpoint, the best place for an isocenter should generally be at the center of PTV. This is especially the case for the intensity-modulated technique, which is composed of a large number of small, elongated, and off-axis segmented fields. Using the off-center technique could result in an increased complexity of the MLC movement. However, this finding helped the host center to better understand the complex relationship between plan complexity and dose delivery.

Although this accuracy survey was aimed nationally, the data were sourced predominantly from RT centers in the national capital, with relatively restricted information being obtained from provincial hospitals. This was the consequence of unforeseen limitations in the form of difficulties shipping the survey equipment, resource unavailability, and time constraints.

6. Conclusions

The expectation of improved outcomes through the use of new, advanced technologies has resulted in the need for high accuracy in the radiation treatment process. In this study, 8 major RT institutes across Thailand demonstrated an excellent quality of IMRT/VMAT for clinical implementation. The IAEA end-to-end test protocol helped us establish a national-level baseline and benchmark of IMRT/VMAT commissioning data.

Financial disclosure

This research have been supported by funding from the International Atomic Energy Agency through the Coordinated Research Project (CRP) titled, "To Investigate the Relationship between End-to-End Accuracy and Quality Assurance Extent and Depth in Radiation Therapy" (CRP E24017).

Conflict of interest

None declared.

Acknowledgements

We are especially grateful to the Thai radiotherapy institutes for participating in this survey, and to the physicists and their teams who helped with the measurements. We also thank the IAEA IMRT workgroup, the Department of Diagnostic and Therapeutic Radiology, Faculty of Medicine, Ramathibodi Hospital Mahidol University, for the film analyses and David Park, for proofreading this manuscript.

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