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A Multicenter Study of IMRT Dosimetry Audit Testing Using C-shape Phantom

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ABSTRACT

Intensity Modulation Radiation Therapy (IMRT) is a complex radiotherapy technique, so independent verification or dosimetry audits must be performed to ensure that accurate dosing is delivered to patients. This study conducted a multicenter audit using a dosimetry audit method developed from the IAEA dosimetry audit for IMRT/VMAT. The phantom in this study is made of acrylic material with two insert structures: planning target volume (PTV) and organ at risk (OAR). Phantom was scanned with a CT simulator at each hospital, and dose distribution was simulated with a PTV prescription dose of 4 Gy/2 fraction (D95 % = 95 %, D2 % < 107 %, and Dmax < 110 %) and a maximum OAR dose of 2.8 Gy. Dose evaluation in this study used TLD-rod for point dose and Gafchromic Film EBT3 for 2D dose distribution. Gamma evaluation was performed for film dose distribution with 3 %/3 mm and 3 %/2 mm criteria. The IMRT dosimetry audit using a C-shape phantom was tested in seven linacs (dynamic and static MLC) from six centers in Jakarta. The TLD results for PTV and OAR point dose show that all 14 IMRT plans meet deviation tolerance within ± 5 %. The film EBT3 evaluation identified that almost all plans pass the minimum 95 % gamma passing rate for 3 %/3 mm criteria and the minimum of 90 % for 3 %/2 mm. Three plans from three centers were also compared to the Gayatri (2022) study data from the same centers. Both results showed that all plans pass the action level ≥ 90 % for both 3 %/2 mm and 3 %/3 mm. Our audit dosimetry study approach employs a small and compact C-shaped phantom and dosimetry, facilitating easier distribution for remote audits. This study could serve as a starting point for remote audits leading to broader multicenter research in Indonesia.

INTRODUCTION

Intensity Modulation Radiation Therapy (IMRT) is an external beam radiation therapy that uses a highly conformal dose distribution that allows for dose escalation in the target volume without increasing the radiation dose to neighboring normal tissues or for a reduction in radiation dose to normal tissues without decreasing the dose to the target [1]. IMRT encompasses the increased use of multileaf collimators (MLCs). With the MLC, the radiation field of irradiation will change according to the tumor's shape from the irradiation direction.

IMRT fields can be delivered with multileaf collimators MLCs by either segmental (sMLC) or dynamic (dMLC) methods. With segmental multi leaf collimation, sMLC, the leaves are stationary while the radiation beam is ON, which means that leaf velocities are unimportant as far as intensity distributions are concerned. This is simpler than dynamic multileaf collimation dMLC, where the

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collimator leaves are moving while the beam is ON; hence, the velocity of the leaves is vitally important. This makes dMLC more complicated to plan and deliver than sMLC. However, dMLC offers more degrees of freedom in the design of intensity distributions.

IMRT is a complex radiotherapy technique that requires a rigorous dose verification procedure [2,3]. Independent verification or dosimetry audits must be performed [4] to ensure that the prescribed dose is delivered to patients accurately. A dosimetry audit is an audit to dosimetrically evaluate if the radiation dose is accurately delivered compared to the dose calculated in the Treatment Planning System (TPS). The clinical use of IMRT in Jakarta supports the need for dosimetry audits of this radiotherapy technique to test normal tissue's dosing accuracy and safety.

Several IMRT verification (dosimetry audit) projects have been carried out in hospitals in several countries. This audit procedure covers dosimetry ranging from point dose measurement, 2D dosimetry with film and/or dosimeter array, to 3D dosimetry [2]. Although IMRT verification is often applied locally in hospitals, some studies show that local QA results do not always match the results of independent audits. A common approach to evaluating dose distribution is using gamma analysis, which in some cases, has shown inconsistencies between results performed with local QA equipment and from independent audits, which usually result in lower pass rates [5].

Kry et al. [5] compared local institutional IMRT patient-specific quality assurance (PSQA) results with those of the Imaging and Radiation Oncology Core at Houston (IROC Houston) phantom results. Although both tools are designed to test the accuracy of IMRT treatment delivery, they found that no PSQA device could reasonably predict whether a plan would fail the IROC Houston phantom. The particularly poor agreement between local PSQA and the IROC Houston phantoms highlights surprising inconsistency in the PSQA process. Inconsistencies between local and independent PSQA results support the need for independent dosimetry audits (in addition to relying solely on local QA measurements) for consistent, accurate, and safe radiation therapy treatments using complex modalities.

IAEA proposed an IMRT dosimetric audit to independently assess the delivered dose using Radio-Photoluminescent Glass Dosimeters (RPLDs) and EBT3 Gafchromic film at the axial plane. The audit phantom had a C-shaped target structure as a Planning Target Volume (PTV) and a cylindrical structure as the Organ at Risk (OAR). Point dose measurements with a 0.6 cm^3 PTW farmer chamber were performed to justify glass dosimetry in IMRT. The measured dose with the RPLDs was compared to the calculated dose in the institution's Treatment Planning System (TPS). They concluded that RPLD was reliable because of its high measurement accuracy compared to PTW farmer chamber measurement. Their study was the first report to justify RPLD's implementation in the IMRT audit in Japan. They also audited the dose distribution with a criterion of 3 %/ 3 mm using EBT3 Gafchromic film evaluation.

The previous multicenter IMRT dosimetry audit in Jakarta was done by Gayatri et al. [6] using the planar dosimetry technique, based on the American Association of Physics in Medical Task Group 119 (AAPM TG-119) protocol. AAPM TG 119 is a protocol to validate the test plans for clinical implementation by comparing the calculated and measured doses for IMRT delivery. AAPM TG-119 has produced quantitative confidence limits as baseline expectation values for IMRT commissioning. A set of test cases was developed to assess the overall accuracy of planning and delivery of IMRT treatments. Each test uses contours of targets and avoidance structures drawn within rectangular phantoms.

The aforementioned multicenter study was performed in four centers in Jakarta. They evaluated the planar dose distribution in the IMRT technique using a standardized acrylic phantom and 2D-ARRAY seven29 detector. Their planar detector was placed horizontally, so in their study, the dose distribution audited was a coronal planar dose. The coronal planar dose was evaluated by comparing the TPS dose and the measured dose in the detector. The gamma index criteria 3 %/3 mm and 3 %/2 mm were used in their study. All participating centers in their research had successfully passed the gamma index passing rate criteria.

This study aims to present a new method and design of dosimetry audit phantoms for IMRT dosimetry audit. We used a new C-shape phantom design and a different dosimeter from the previous study. This phantom was developed from the IAEA dosimetry audit phantom design [2]. We audited axial planar dose distribution using EBT3 Gafchromic film and audited point dose using thermo-luminance dosimeters (TLDs). This proposed audit method was tested in seven linacs (dMLC and sMLC) from six centers in Jakarta. The proposed C-shape phantom design and dosimetry evaluation are expected to be used as an on-site audit. The advantage of an on-site audit is that any error found can be traced to the cause.

METHODOLOGY

C-shape phantom

The C-shape phantom design was inspired by the C-shape audit phantom developed by IAEA. We copy the sandwich design of body and insert unit. The body and insert unit are shown in Fig. 1. The "body" unit measures 15 × 15 cm with a total thickness of 15 cm and is made from PMMA (mass density 1.17 g/cm^3). The body unit is divided into three parts to insert Thermoluminescent Dosimeter (TLD) and film on the holder easily.

The body and insert unit was made using 15 pieces of 1 cm-thick PMMA slab. Every piece of it was cut using laser, and then combined with PMMA glue as the design we proposed.

Each part of body unit has a thickness of 5 cm, meaning that everybody unit was made of 5 pieces of PMMA glued slab. Two parts of insert unit have size of 6 × 6 cm^2 with a thickness of 3 cm each. Every insert part was cut using laser as we designed to be PTV and OAR. The PTV and OAR design is different from IAEA audit phantom. The proposed design was inspired by C-shape structure set from AAPM TG-119. The PTV and OAR cut part was made a hole, then filled with a mixture of resin and carbon (mass density 1.19 g/cm^3).

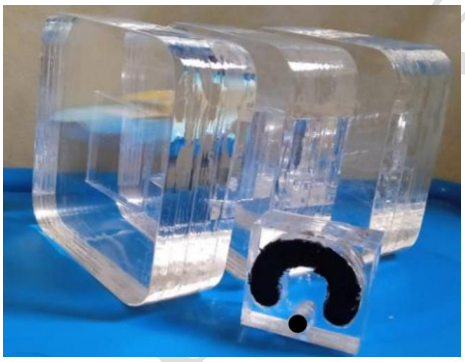

Fig. 1. C-shape phantom used in this study 6.

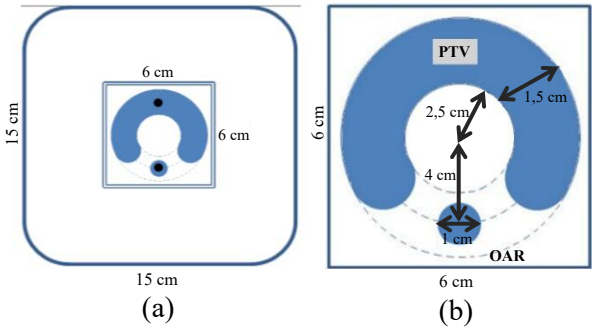

Fig. 2. (a) IMRT dosimetry audit phantom design cross-section; (b) PTV and OAR insert size details.

The mixture was supposed to make higher Hounsfield Unit (HU) to PMMA, so that we can create the contour of PTV and OAR for radiation planning purposes. One part of insert unit was drilled using drill machine to make a holder (5 mm diameter and 5 mm depth) to place TLDs in each PTV and OAR. The 3 pieces of TLDs were inserted in a holder, as shown in Fig. 2.

Dosimetry

This study used two dosimeters, namely TLD-100 rod Harshaw and Gafcromic Film EBT3. TLD-100 Harshaw is rod-shaped with 1 mm in diameter and 3 mm in length. This TLD is composed of LiF, Mg, and Ti materials. This TLD was read using the Harshaw TLD reader and WinREMS software. Three TLDs were used at each point. EBT3 Gafchromic film determines the dose distribution resulting from IMRT irradiation. On the other hand, the film was read using a film scanner and processed using ImageJ, Matlab, and Verisoft software. Dose distribution was evaluated using gamma analysis with criteria 3 % dose difference, 3 mm distance-to-agreement, 20 % dose threshold, global gamma, and 90 % minimum pass rate as suggested by IAEA [2]. We also evaluated dose distribution with criteria of 3 % dose difference, 2 mm distance-to-agreement, 10 % dose threshold, and global gamma to compare the results with previous study data from the same centers [6]. Both dosimeters have been calibrated at a depth of 5 cm phantom slab, with a beam field of 10 × 10 cm^2 and a variation of 50-600 monitor unit (MU), with interval of 50 MU.

An MU is a unit that quantifies the amount of radiation delivered. All linac output should be calibrated to 1cGy/MU at maximum depth under reference condition (measured in water or its equivalent; 10 × 10 cm^2 field size, 100 cm Source to Surface Distance (SSD)).

Treatment Planning System (TPS) simulation

The simulation was conducted at two TPSs (Monaco and Eclipse) in different centers. We simulated the C-shape phantom design reasonably met all planning criteria. We also simulated a 1 mm isocenter shift to estimate the shift effect on dosimetric evaluation. The simulated shifts are longitudinal, lateral, and vertical ± 1 mm shifts.

Multicenter study

This study was conducted at six hospitals in Jakarta with seven linacs (4 VARIAN linacs and 3 ELEKTA linacs). We tested both sMLC and dMLC techniques for five linacs in four centers. We only tested the dMLC technique for the other two centers (Center-1 and Center-2) because dMLC was their only clinical beam delivery technique. The audit process was carried out on-site using the same phantom. Phantom is treated using each hospital's patient treatment protocol. First, phantom CT images were taken per hospital protocol. Furthermore, radiation treatment planning is carried out with the following requirements: Five gantry angles with photon energy 6 MV; Prescription dose is 4 Gy in 2 fractions; On PTV, $D_{95\,\%} > 95$ %, $D_{2\,\%} < 107$ %, and $D_{max} < 110$ %; On OAR, $D_{max} < 2.8$ Gy.

In this paper, $D_{x\,\%}$ refers to the percentage of prescribed dose that covers x % volume PTV. D_{max} refers to the maximum dose that PTV or OAR can receive.

Patient-specific QA is carried out per hospital protocol. Next, the phantom is irradiated by two fractions without repositioning. TLD readings and Film scans are carried out within 24-48 hours post-irradiation.

RESULTS AND DISCUSSION

TPS simulation result

All planning criteria were successfully achieved in three IMRT planning process simulations. The time needed for each planning (including body, OAR, and PTV contouring) is 30-60 minutes. The simulation process was done quickly to meet all planning criteria, proving that the phantom design was feasible and could meet the planning protocols.

The simulation of the 1 mm shift at the TPS showed that the difference of 1 mm did not cause a significant deviation in the gamma evaluation with the criteria of 3 %/3 mm. The passing rate is in the range of 99.3-100 %. At point doses, the largest deviation was 3.2 %, i.e., on TPS-1 with + 1 mm vertical shifting for OAR doses. The simulation of the 1 mm shift at the TPS showed that the 1 mm difference did not result in a significant deviation, namely < 1 % for gamma evaluation and < 5 % for point dose deviation. In addition, non-deformed C-shape phantom underlies our decision not to evaluate patient positions with CBCT or 2D images.

So, in this study, the data obtained were not influenced by the difference in dose from imaging with the kV source of each center. We confirmed no isocenter-shift more than 1 mm during the phantom positioning process. However, it should be emphasized that the 1 mm shift is negligible if there is no steep-gradient dose within a 3 mm radius of the PTV and OAR TLD inserts and gamma evaluation is carried out with a 2 mm or larger distance to agreement criteria.

Dosimetry result

Each center has verified the internal planning of this study by conducting PSQA using each center's detector array. All centers have stated that the IMRT plan has passed the internal PSQA. The PSQA pass rate ranges from 98 % to 100 % in criteria 3 %/3 mm and 95 % to 100 % in criteria 3 %/2 mm.

Point dose measurement with TLD has been conducted in seven linacs of six radiotherapy centers in Jakarta. From the data obtained (shown in Table 1), all point dose data on OAR are below the maximum dose limit of OAR 2.8 Gy with a range of 2.22–2.55 Gy, and the measured PTV point dose was in the range of 4.04–4.26 Gy. All TLD measurement deviations are between -5 % and + 5 %, as shown in Fig. 3. In film evaluation, all seven linacs audited passed the 3 %/3mm gamma criterion with a passing rate above 95 % and 90 % for the 3 %/2 mm criteria (shown in Fig. 4). This TLD and film evaluation results indicate that all seven linacs had good IMRT performance.

Table 1. TLD measurements results.

Center	MLC	TPS_OAR (Gy)	TLD_OAR (Gy)	TPS_PTV (Gy)	TLD_PTV (Gy)
1	dMLC	2.56	2.51 ± 0.06	3.98	4.09 ± 0.07
2	dMLC	2.61	2.52 ± 0.08	3.94	4.04 ± 0.11
3	dMLC	2.32	2.39 ± 0.01	4.09	4.26 ± 0.02
	sMLC	2.23	2.29 ± 0.01	4.10	4.22 ± 0.03
4	dMLC	2.36	2.42 ± 0.01	4.10	4.19 ± 0.02
	sMLC	2.24	2.27 ± 0.02	4.10	4.18 ± 0.03
5	dMLC	2.58	2.55 ± 0.04	4.18	4.14 ± 0.05
	sMLC	2.53	2.51 ± 0.01	4.21	4.19 ± 0.01
6	dMLC (1)	2.34	2.44 ± 0.02	4.05	4.17 ± 0.02
	sMLC (1)	2.29	2.37 ± 0.03	4.09	4.24 ± 0.01
	dMLC (2)	2.18	2.26 ± 0.04	4.14	4.18 ± 0.02
	sMLC (2)	2.17	2.22 ± 0.01	4.15	4.16 ± 0.00

(1) Linac-1; (2) Linac-2

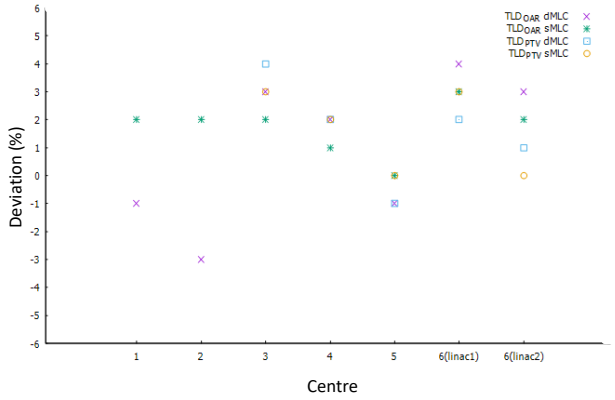

Fig. 3. Distribution of TLD relative deviation to TPS value. Red line is tolerance limit ±5 % deviation.

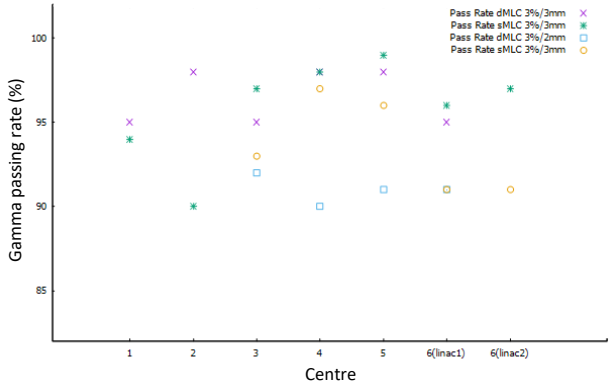

Fig. 4. Distribution of gamma pass rate from 6 center. Blue line is 95 % pass rate and red line is 90 % pass rate.

The sMLC plan deviation was 2.04 ± 1.26 % in the TLD evaluation, and the pass rate was 96.36 ± 2.46 % in the film evaluation. In comparison, the dMLC plan deviation was 2.62 ± 1.24 % in the TLD evaluation, and the pass rate was 94.03 ± 3.25 % in the film evaluation. We used a paired t-test with a 95 % confidence limit to statistically compare dMLC. The paired t-test result shows that sMLC and dMLC plans had significant differences, with p-values of 0.035 for distribution evaluation (film evaluation) and 0.025 for point dose evaluation (TLDs evaluation). It appears that sMLC plans had a more minor deviation and higher gamma passing rate than dMLC plans. The sMLC plan delivery approach may be less fraught with problems associated with dynamic motion, i.e., variable leaf speed control, gap separation stability, and possible motor fatigue. The sMLC plans also uses fewer MUs, resulting in fewer transmission and activation problems [7].

Table 2. Comparison gamma analysis data from three same centers.

Center	Gamma criteria 3 %/ 3mm			Gamma criteria 3 %/2 mm		
	dMLC	sMLC	Gayatri et.al (2022)	dMLC	sMLC	Gayatri et.al (2022)
3	95.8	97.4	99.7	92.0	93.6	96.3
4	98.0	98.3	99.9	90.2	97.1	98.1
6 (linac1)	95.5	96.9	100.0	91.3	91.7	100.0

We also compared our data with Gayatri et al. [6] multicenter study using AAPM TG-119, as shown in Table 2. We compared three of the same centers, i.e., center-3, center-4, and center-6, respectively named as center-E, center-B, and center-C in their paper. Both results showed that all plans had a lower pass rate for 3 %/2 mm than 3 %/3 mm but still passed the action level ≥ 90 % for both 3 %/2 mm and 3 %/3 mm, as suggested by AAPM TG-218 [8] and IAEA [2]. Thus, these results show that those three linacs from the three centers are still performing well in IMRT radiation delivery after the three-year audit gap.

We found that this study's pass rate is lower than that of the previous study. However, we cannot conclude the reason for this study's lower results than their study. Both studies evaluated different dose plans. We evaluated the axial plane dose, while Gayatri et al. evaluated the coronal plane dose. We also used different dosimetry to evaluate the plane dose than the dosimetry that Gayatri et al. used in their study [6].

Gayatri et al. [6] study also explained the multicenter study using AAPM TG-119, which was faster and simpler to evaluate the dose distribution without any post-processing dosimetry, while film EBT-3 needed more time for post-processing to be able to be evaluated. However, the dosimetry audit process with the AAPM TG-119 protocol must be carried out with an on-site audit process because the detector array used is quite expensive and difficult to distribute for remote audits.

Our audit dosimetry study method uses a small-sized C-shape phantom and dosimetry, making it easier to distribute for remote audits. Furthermore, this new dosimetry audit method has a high-accuracy evaluation with a high-level 3 %/2 mm gamma analysis criteria and a small-level ± 5 % TLD tolerance deviation. Thus, this study can be the beginning of a remote audit for further research on a broader multicenter scale in Indonesia.

CONCLUSION

This study performed an IMRT multicenter audit using a C-shape phantom, TLD rod, and film EBT3, a developed method from the IAEA dosimetry audit. All participating centers in this study had good IMRT irradiation performance with TLD reading deviation below ± 5 % and pass film evaluation with gamma passing rate above 90 % for 3 %/2 mm criteria and 95 % for 3 %/3 mm criteria, both for sMLC and dMLC plan. Our audit dosimetry study approach employs a small and compact C-shaped phantom and dosimetry, facilitating easier distribution for remote audits. This study could serve as a starting point for remote audits leading to broader multicenter research in Indonesia.

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AUTHOR CONTRIBUTION

Brigitha Dwinesti and Supriyanto Ardjo Pawiro were the main contributors to this paper. Dea Ryangga, Fransisca Dimitri, Andrian Dede Handika, Muhammad Fadli, Aloysius Mario Yudi Putranto, and Soeharsono contributed to data curation. Supriyanto Ardjo Pawiro contributed to formal analysis, funding acquisition, conceptualization, supervision, review and editing.

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