Pretreatment Dose Verification in Volumetric Modulated Arc Therapy Using Liquid Ionization Chamber

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Abstract

Purpose: The purpose of the present study was to evaluate the practicability of liquid ionization chamber (LIC) for pretreatment dose verification of the advanced radiotherapy techniques such as volumetric modulated arc therapy (VMAT). **Materials and Methods:** The dosimetric characteristics of LIC such as repeatability, sensitivity, monitor unit linearity, dose rate dependence, angular dependence, voltage-current response, and output factors were investigated in 6 MV therapeutic X-ray beams. The LIC was cross-calibrated against 0.125-cc air-filled thimble ionization chamber. A dedicated dosimetry insert made up of Perspex to incorporate the LIC at proper location in the intensity-modulated radiation therapy thorax phantom was locally fabricated. The collection efficiency and ion recombination correction factor was determined using the two-dose rate method. Pretreatment dose verification measurement of VMAT treatment plans were carried out using the liquid ionization chamber as well as small volume (0.125 cc) air-filled thimble ionization chamber. The measured dose values by the two dosimeters and TPS calculated dose at a given point were compared. **Results:** The relative percentage differences between the TPS calculated and measured doses were within ± 1.57% for LIC and ± 2.21% for 0.125 cc ionization chamber, respectively. **Conclusions:** The measured dose values by the two dosimeters and TPS calculated dose at a given point were found comparable suggesting that the LIC could be a good choice of dosimeter for pretreatment dose verification in VMAT.

Keywords: Collection efficiency, dose verification, liquid ion chamber, volumetric modulated arc therapy

INTRODUCTION

Volumetric modulated arc therapy (VMAT) is a novel and advanced form of radiation therapy technique.[1] The VMAT technique delivers intensity-modulated radiation beams simultaneously changing the gantry rotation, dose rate, and multileaf collimator (MLC) shape along with its motion.[2] Several authors[3-5] have reported that the VMAT technique can produce better dose conformity, homogeneous dose distribution inside the target volume, and adequate sparing of organs-at-risk with a shorter treatment time than intensity-modulated radiation therapy (IMRT). The presence of many dose gradients within the treatment fields as well as the contribution of manifold intensity-modulated small fields from different directions results in altogether different dosimetry treatment parameters such as monitor unit (MU), MLC positioning, and its motion for each patient. These parameters may vary significantly among patients undergoing the treatment with VMAT.[6] Patient-specific pretreatment dose verification of IMRT/VMAT is strongly recommended for all patients in order to detect any potential errors in treatment planning process as well as treatment delivery and it is thus performed routinely.[7] The pretreatment dose verification provides information about dose computation accuracy of treatment planning system (TPS), accuracy in transfer of plan parameter from TPS to the treatment console and MLC for each plan. Patient-specific pretreatment dose verification is routinely performed by means of measurement of radiation absorbed dose at reference point using small volume air-filled ionization chamber[8] and the two-dimensional dose distribution analysis with the help of radiochromic films,[9,10] electronic portal imaging devices,[11,12] and array of ion chambers.[13,14]

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The air ionization chamber (AIC) uses low-density air medium in sensitive volume which generate limitations when developing a small volume chamber, and its response can be influenced by the volume averaging effect.[15] A low-density air cavity within a high-density water medium also perturbs the electron fluence.[16] Conversely, liquid ionization chambers (LICs) have high-density medium (iso-octane, density: 0.688 g/cc vs. air, density: 0.001293 g/cc) which can allow to fabricate very small sensitive volume. The higher density of the liquid (density of liquid is nearly 500 times higher than the air) greatly increases the ionization density and thus the sensitivity (response per unit dose) of the chamber compared to that of air-filled detector of the same volume is relatively high.[17] Since the density of liquid is close to that of water, the influence of perturbation effects can be minimal. Therefore, LIC can be a good choice of dosimeter for pretreatment dose verification in VMAT.

In this work, dosimetric properties of a commercial LIC were evaluated and its suitability for pretreatment dose verification of VMAT treatment plans were studied in comparison to air-filled ionization chamber.

MATERIALS AND METHODS

Ionization chambers

The PTW microLion LIC, (Type 31018, PTW Freiburg, Germany) having sensitive volume of 0.0017cc, was used for this study. The radius and depth of the sensitive volume of the LIC are 1.25 mm and 0.35 mm respectively. LIC is filled with iso-octane liquid (2,2,4-trimethylpentane) and the density of liquid is 0.688 g/cc. The reference point of measurement is located at 0.975 mm from the entrance window of the chamber. The stand-alone high voltage supply, PTWHV-SUPPLY T16036 (PTW Freiburg, Germany) was used for applying the bias voltage and calibrated UNIDOS webline electrometer (PTW Freiburg, Germany) was used for measurement. The LIC was operated at a bias voltage of 800 V. The dosimetry system was kept in ready state for 30 min to attain the desired electrical stability, and the chamber was preirradiated for 6 Gy before its use in intended measurement. The AIC (Model 1041, Sun Nuclear Corporation, Melbourne, Florida) having sensitive volume of 0.125 cc was used for cross-calibration of liquid ion chamber and comparison of pretreatment dose verification. The technical specifications of these dosimeters are given in Table 1. The 6 MV X-rays with flattening filter (6 WFF) beams from TrueBeam medical electron linear accelerator (Varian Medical System, Inc., Palo Alto CA) was used in this study. This accelerator contains 120-leaves MLC (Varian HD-MLC with projected leaf widths of 2.5 mm at the center and 5 mm in the periphery) for shaping the X-ray beam.

Intensity-modulated radiation therapy thorax phantom

For pretreatment dose verification, an IMRT thorax phantom, (Model002 LFC, CIRS, Virginia, USA) which is elliptical in shape representing an average human torso in proportion, density, and shape was used. It measures 30 cm long × 30 cm wide × 20 cm thick. The phantom is constructed from tissue equivalent epoxy materials. This heterogeneous thorax phantom consists of different materials, representing tissues inside the thorax such as the lungs, spinal cord, and soft tissue. It has tissue equivalent interchangeable rod inserts which accommodate the 0.125 cc ionization chamber allowing for point dose measurements within the phantom. A dedicated dosimetry insert made up of Perspex to incorporate the LIC at proper location in the IMRT thorax phantom was locally fabricated. Figure 1 shows the photograph of CIRS IMRT thorax phantom and the removable dosimetry insert to position LIC.

Dosimetric characteristics of liquid ionization chamber

The dosimetric characteristics which include repeatability, sensitivity, dose response, linearity, dose rate dependence, angular dependence and voltage-current (V-I) characteristics of LIC were studied. The repeatability and sensitivity of 0.125 cc AIC was also studied and sensitivity of both the detectors were compared. Measurements related to dosimetric characteristics of the dosimeters were performed in 1D scanning phantom (Sun Nuclear Corporation, Melbourne, Florida). The detector was placed in 1D scanning water phantom at 5 cm depth and irradiated using field size of 10 cm × 10 cm with source to surface distance (SSD) at 100 cm. The sensitivity of the detector was calculated by taking the ratio of the response per unit dose (nC/Gy). The sensitivity measurement for LIC was carried out in two different orientations with respect to beam axis, namely, (i) parallel orientation and

Table 1: Technical specifications of PTW microLion 31018 liquid-filled ionization chamber and Sun Nuclear Corporation 1041 air-filled ionization chamber

Specification	MicroLion 31018	SNC 1041
Sensitive volume (cc)	0.0017	0.125
Operating voltage (V)	800	300
Nominal response (nC/Gy)	9.8	3.4

SNC: Sun Nuclear Corporation, PTW: Physikalisch technische werkstätten

Figure 1: Photograph of CIRS intensity-modulated radiation therapy thorax phantom and the removable dosimetry insert: (a) CIRS intensity-modulated radiation therapy thorax phantom, (b) insert for air ionization chamber available from CIRS, and (c) fabricated insert for liquid ionization chamber

(ii) perpendicular orientation. The sensitivity measurement for AIC was carried out only in perpendicular orientation. For all other measurements, LIC was positioned in perpendicular orientation.

A repeatability test was designed in order to verify the short-term reproducibility of the output of the detector. The radiation doses of 100 cGy at a time interval of 2 min were delivered. The irradiation was repeated for ten times and coefficient of variation (CoV) was calculated using the formula:

CoV = Standard deviation/mean   (1)

The linearity in response was performed over a wide range starting from 5 to 2000 MUs of the accelerator. The MUs of 5, 10, 15, 20, 25, 50, and 100 were chosen in lower MU range. The higher MU range contains 200, 500, 1000, and 2000. The coefficient of linearity (CoL) was calculated from average response per unit MU using the formula:

CoL = $([X_{max} - X_{min}]/[X_{max} + X_{min}])$ (2)

where X_{max} and X_{min} are the maximum and minimum response per unit MU over the entire MU range.

The dose rate dependence of LIC was studied with dose rates of 60, 100, 200, 300, 400, 500, and 600 MU/min. The LIC response for various dose rates was measured and response was normalized at clinically used dose rate of 400 MU/min.

The V-I characteristics of LIC was studied by delivering 100 MU for different bias voltages ranging from 25 to 800 V. The bias voltages applied during the measurement were 25, 50, 100, 200, 300, 400, 500, 600, 700, and 800 V, respectively.

The angular dependence of the LIC was investigated for 6 MV X-ray beam by positioning the detector at source to axis distance of 100 cm. The LIC was placed perpendicular to the beam axis. The gantry angle was varied from 0° to 360° with an increment of 45°. In addition, the reading at gantry angle 30° and 330° were also taken. The angular dependence was investigated for field size of 3 cm × 3 cm and 10 cm × 10 cm, respectively. The percentage variations were calculated by normalizing the reading at gantry angle of 0°.

Cross-calibration of liquid ionization chamber and measurement of output factor

The LIC presents a cylindrical cavity with a small sensitive thickness (0.35 mm), but it has larger sensitive diameter (2.5 mm); this means that the response of chamber may depend on the type of measurement and the orientation of the detector with respect to the beam direction. Therefore, the LIC was cross-calibrated against AIC in two different orientations, namely (i) parallel orientation and (ii) perpendicular orientation as shown in Figure 2. The LIC and AIC were positioned at 10 cm depth in a water phantom using SSD set up (SSD = 100 cm) and irradiated using 10 cm × 10 cm field size. The cross-calibration was performed as per the procedure outlined in the IAEA Technical Report Series 398 (TRS 398).[18]
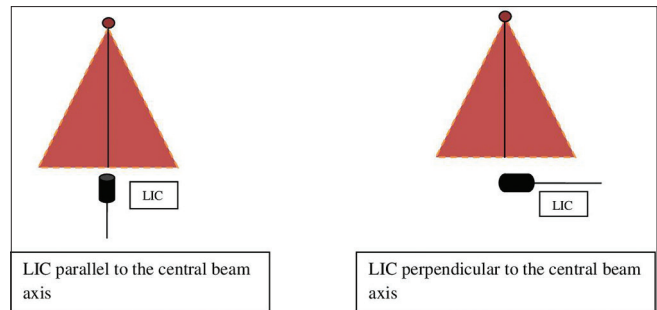

Figure 2: Schematic diagram showing experimental setup used during cross-calibration of the liquid ionization chamber in parallel and perpendicular orientations

The cross-calibration factor of perpendicular orientation was used for estimating the dose by LIC during VMAT dose verification.

The LIC was used to measure relative output factor of 6 MV X-ray beam. The output factor measurements were carried out by delivering 100 MUs for squared field sizes ranging from 1 cm × 1 cm – 40 cm × 40 cm.

General recombination correction factor

The accurate knowledge of general recombination and its correction is important for IMRT QA using LIC.[19] The two-dose rate method suggested by Wagner *et al*.[17] was employed for the determination of collection efficiency and ion recombination factor. The two-dose rate method involves the irradiation of the dosimeter using 100 MU by varying SSD from 90 to 120 cm. In this measurement, both LIC and AIC were placed side-by-side in a water phantom at a depth of 1.5 cm and irradiated using 10 cm × 10 cm field size from 6 MV X-rays. Five readings were taken at each SSD to assess the uncertainty. Under the reference conditions (100 cm SSD, 10 cm × 10 cm field size), the dose per pulse for 6 WFF X-rays is given by the relation:

Dose/pulse = (600 [cGy/min])/(360 [Hz] × 60 [sec/min]) = 0.28 mGy/pulse   (3)

where 360 Hz is the pulse repetition frequency of the accelerator which was used in this work. For calculating dose per pulse other than 100 cm SSD, appropriate correction based on inverse square law was applied. Accordingly, dose per pulse at 90 cm and 120 cm SSDs were 0.345 mGy/pulse to 0.19 mGy/pulse, respectively.

Dosimetric verification of volumetric modulated arc therapy plans

The computed tomography (CT) images of the IMRT thorax phantom with insert for AIC and LIC respectively were taken one by one with 2.5-mm slice thickness using a CT scanner (Discovery CT590 RT, GE Medical Systems Asia, USA). These images were transferred to Eclipse TPS (v13.7, Varian Medical System, USA) through DICOM network. The pretreatment dose verification plans simulating the treatment of five different patients to be treated by double-arc VMAT

using 6 WFF beams were generated using Eclipse TPS. Two sets of pretreatment verification plans were generated, the first set using CT images with the AIC as insert in IMRT thorax phantom and the second using CT images with the LIC as insert in the IMRT thorax phantom. The dose values to specific points were calculated using anisotropic analytical algorithm and 2.5 mm grid size and the value so obtained were recorded as TPS calculated dose. The dose to points where TPS dose values are recorded were also measured using LIC and AIC in IMRT thorax phantom. The TPS calculated and LIC as well as AIC measured dose values were intercompared.

RESULTS

Dosimetric characteristics

The sensitivity of LIC (0.0017 cc, perpendicular orientation) and AIC (0.125 cc) is found to be 10.14 nC/Gy and 3.47 nC/Gy, respectively. It indicates that the sensitivity of the LIC is 2.92 times higher than the sensitivity of AIC. The repeatability in the measurement was quantified using CoV, and it was found to be 0.02%. The cross-calibration coefficient for parallel and perpendicular orientation was found to be 9.82 cGy/nC and 9.62 cGy/nC, respectively. The percentage difference of

2% was found in cross-calibration factor for parallel versus perpendicular orientation.

The MU linearity of the LIC is shown in Figure 3. The CoL over a wide MU range starting from 5 to 2000 MU was found to be 0.0016.

The output factors were measured using LIC for the square fields with sides of 1, 2, 3, 4, 5, 7, 10, 12, 15, 18, 20, 25, 30, 35, and 40 cm. Figure 4a presents the measured output factors for 5 cm × 5 cm – 40 cm × 40 cm (measured as per TRS 398) and Figure 4b presents the measured output factors for field sizes 1 cm × 1 cm – 4 cm × 4 cm (measured as per TRS 483). The measured output factors for TrueBeam 6 MV FF beam measured with LIC are consistent with the result of Glide-Hurst *et al*.[20] for small field sizes ranging from 1 cm × 1 cm – 4 cm × 4 cm as well as field size >4 cm × 4 cm.

The LIC response for various dose rates ranging from 60 to 600 MU/min for 6 MV photon beams normalized at 400 MU/min is shown in Figure 5. The maximum deviation was found to be 0.36%. The results obtained show that the response of the chamber is almost independent of dose rate used in this work.

The V-I characteristic of the LIC over the voltage range studied is shown in Figure 6. It is observed that the response of the LIC does not saturate at higher voltages contrary to the well-known response of AIC.

The results of studies carried out for quantifying the angular dependence of LIC in perpendicular orientation for field sizes 3 cm × 3 cm and 10 cm × 10 cm are shown in Figure 7a and b respectively. It is observed from these figures that the angular dependence of LIC in perpendicular orientation for field sizes 3 cm × 3 cm and 10 cm × 10 cm are within ± 0.54% and ± 0.57%, respectively.

General recombination correction factor

The collection efficiency of liquid ion chamber against the dose per pulse values determined with the help of two dose rate method is shown in Figure 8. The dose rate of 600 cGy/min corresponds to dose per pulse value of 0.28 mGy/pulse. The two-dose rate method employed in this study does not offer the absolute values of collection efficiency. The collection
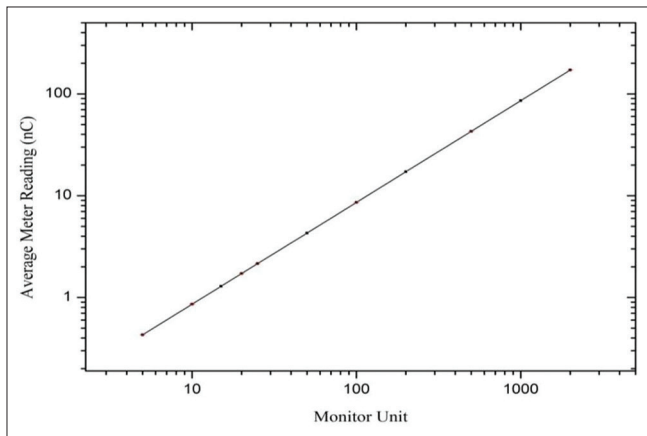

Figure 3: Linearity in response of the liquid ionization chamber with respect to varying monitor unit of the X-ray beam
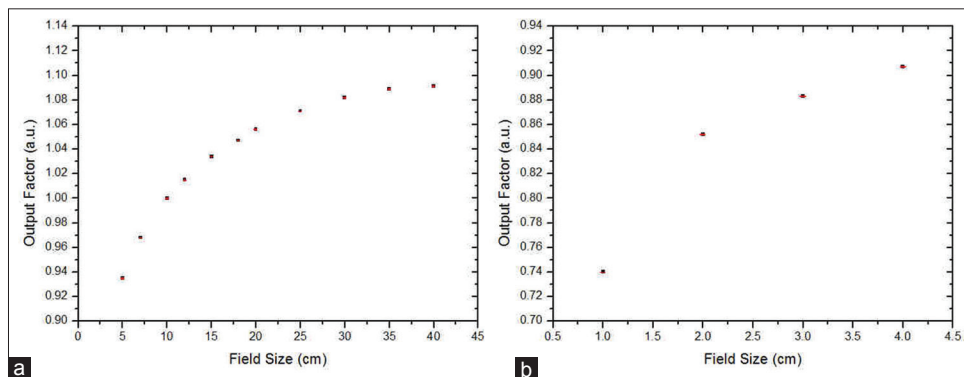

Figure 4: (a) Measured output factors of 6 MV X-rays of TrueBeam electron medical linear accelerator from 5 cm × 5 cm to 40 cm × 40 cm using liquid ion chamber. (b) Measured output factors of 6 MV X-rays of TrueBeam electron medical linear accelerator from 1 cm × 1 cm to 4 cm × 4 cm using liquid ion chamber
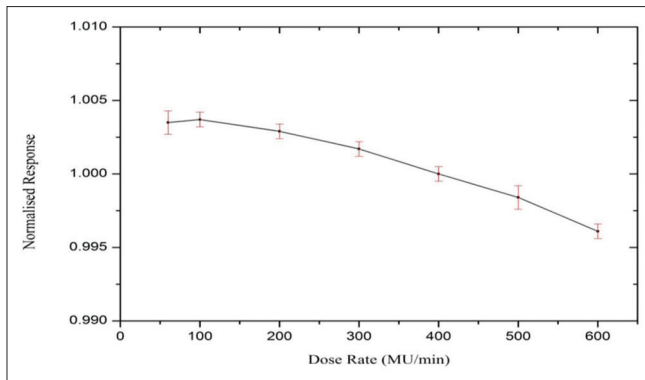
Figure 5: Relative response of the liquid ionization chamber at different dose rates of 6 MV X-ray beam

Figure 6: Voltage-current (V-I) characteristic of the liquid ionization chamber

efficiency was obtained by assuming no-recombination at 0 mGy/pulse and interpolating the ratio of charge measured using LIC and AIC (Q_{LIC}/Q_{AIC}) at different dose per pulse to 0 mGy/pulse.

The collection efficiency at 0 mGy/pulse was considered as 1 and other values were normalized accordingly. The collection efficiency shows linear behavior with respect to the dose rate. The collection efficiency drops to 0.9823 for a clinical dose rate of 600 cGy/min (0.28 mGy/pulse).

Dosimetric verification in volumetric modulated arc therapy

The relative percentage difference between the TPS calculated and measured dose with LIC for five VMAT pretreatment dose verification plans are shown in Table 2. Table 3 shows the relative percentage difference between the TPS calculated and measured dose with AIC. The relative percentage difference between the TPS calculated and measured dose values are within ± 1.57% for LIC and ± 2.21% for ionization chamber, respectively.

DISCUSSION

Practicability of using liquid-filled ion chamber for pretreatment dose verification of the advanced radiotherapy techniques such as VMAT with 6 MV flattened beam was investigated. The sensitivity of LIC and AIC were 10.14 and 3.47 nC/Gy, respectively, that is, sensitivity of LIC (0.0017 cc) is 2.92 times higher than the sensitivity of AIC (0.125 cc). It is worth mentioning that volume of LIC is much lower than volume of AIC. The LIC presents a high sensitivity compared to AIC due to the fact that the liquid used in LIC has a higher density of charge carriers generated from the ionization process. Production of higher density of charge carriers in LIC is attributed to higher density of iso-octane compared to air and less energy required to produce one ion pair (w/e). These features of LIC make it suitable for manufacturing a dosimeter of miniature size. The miniature size of dosimeter has several advantages for small-field dosimetry.[21] As VMAT/IMRT fields are combination of small and irregular radiation beam portal,
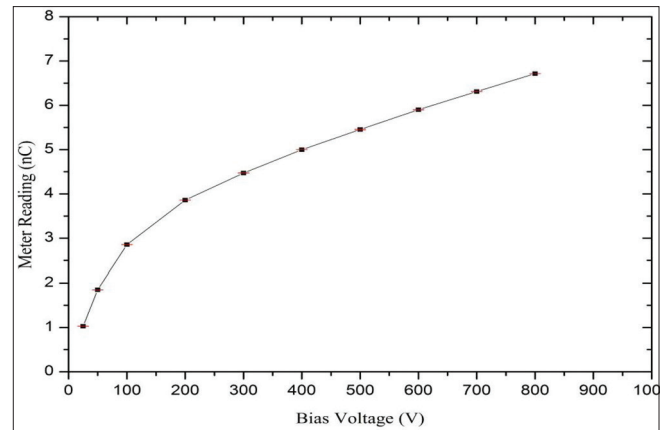
Table 2: In-phantom measured dose values simulating the treatment condition of patients treated by volumetric modulated arc therapy using PTW microLion 31018 liquid-filled ionization chamber and the relative difference with respect to treatment planning system calculated dose

Patient ID	LIC measured dose (cGy)±SD	TPS calculated dose (cGy)±SD	Difference (%)
P1	211.06±0.69	211.40±0.40	−0.16±0.004
P2	213.76±0.35	215.60±2.00	−0.86±0.009
P3	237.26±0.35	236.60±1.80	0.28±0.008
P4	227.96±1.04	231.60±3.00	−1.59±0.016
P5	93.53±0.69	95.00±2.80	−1.57±0.033

TPS: Treatment planning system, LIC: Liquid ionization chamber, SD: Standard deviation, PTW: Physikalisch technische werkstätten

Table 3: In-phantom measured dose values simulating the treatment condition of patients treated by volumetric modulated arc therapy using Sun Nuclear Corporation 1041 air-filled ionization chamber and the relative difference with respect to treatment planning system calculated dose

Patient ID	AIC measured dose (cGy)±SD	TPS calculated dose (cGy)±SD	Difference (%)
P1	211.98±0.66	210.70±0.90	0.61±0.006
P2	212.47±0.81	215.50±2.20	−1.43±0.012
P3	230.30±0.40	235.40±1.30	−2.21±0.007
P4	228.88±0.40	230.50±2.00	−0.70±0.009
P5	97.26±1.00	96.00±3.60	1.30±0.040

TPS: Treatment planning system, SD: Standard deviation, AIC: Air ionization chamber

small size and large sensitivity detectors are considered as suitable choice for dose verification. Considering this fact, LIC has been explored as a choice of detector for pretreatment dose verification in VMAT/IMRT. For sake of completeness, comprehensive dosimetric characteristics which include dose rate dependence, output factor, and MU linearity of the chamber were studied before applying for dose verification
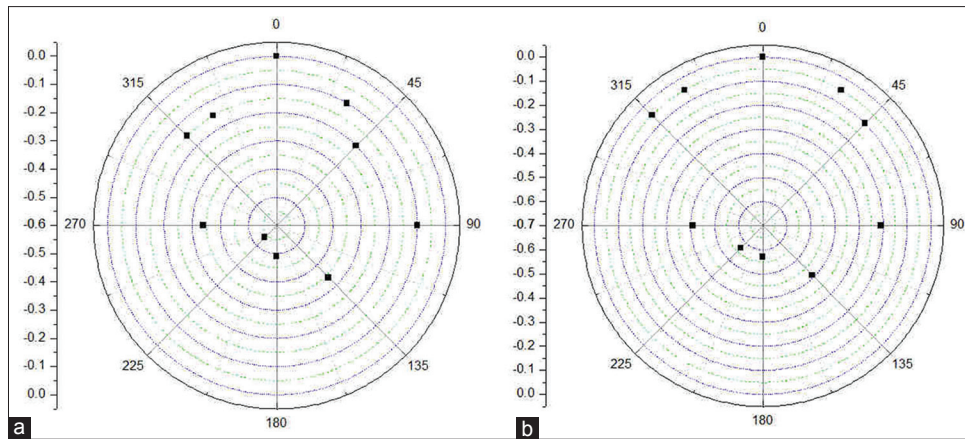
Figure 7: (a) The angular dependence of liquid ion chamber in perpendicular direction for 3 cm × 3 cm field size. (b) The angular dependence of liquid ion chamber in perpendicular direction for 10 cm × 10 cm field size
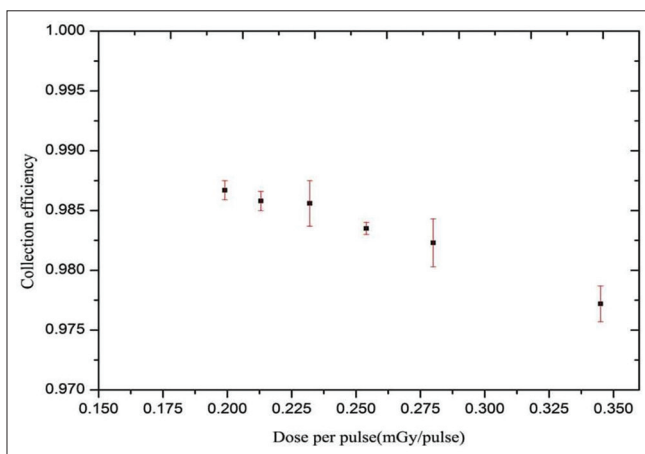

Figure 8: Collection efficiency of the liquid ionization chamber

application. The V-I response of the LIC indicates that its response goes on increasing with the increase in the applied bias voltage which is contrary to the response of AIC which saturates at higher bias voltage (around 200 V). The LIC is affected by the initial and general recombination effects due to higher density of the liquid medium and lower ion mobility.[22] The positive and negative ion mobility for iso-octane are 2.9×10^{-8} $m^2s^{-1}V^{-1}$ according to Johansson and Wickman,[23] while the positive and negative ion mobility for air is 2.10×10^{-4} $m^2s^{-1}V^{-1}$ and 1.36×10^{-4} $m^2s^{-1}V^{-1}$, respectively, as given by Boag.[24] The low ion mobility of iso-octane liquid leads to high possibility of ion recombination and necessitate suitable correction. The two-voltage technique described in AAPM's TG 51 or IAEA TRS 398 which is used universally for AICs is not valid for evaluating ion recombination effect in liquids. With the objective of using the liquid ion chamber for pretreatment dose verification, it is necessary to find out the collection efficiency and ion recombination correction factor (inverse of collection efficiency). Some authors[25,26] have estimated the collection efficiency using the formula based on Boag's theory for a pulsed beam and few researchers[27-29] described an approach for estimating the recombination losses in pulsed beams and continuous beam

using two dose rate methods. The general recombination in liquids depends on the dose per pulse therefore application of two dose rate method instead of two voltage method for the collection efficiency and ion recombination correction factor determination was recommended for use during pretreatment dose verification. Ion recombination correction factors measured with two-dose rate method were in line of the earlier reported values.[17]

The liquid chamber can be used for pretreatment dosimetric verification of VMAT plans. However, the cost of liquid ion chamber is relatively high in comparison to small-volume air-filled ionization chambers. Further, liquid ion chamber-based system requires application of high voltage of the order of about 800 volts, which needs an extra high voltage supply. Hence, specialized and dedicated electrometer is required to fulfill this requirement. The operating, working, and handling procedures of both the systems are different, but both the systems are easy and convenient to use in clinical practice.

CONCLUSIONS

The dosimetric characteristics of microLion LIC (Type 31018, PTW Freiburg, Germany, volume 0.0017 cc) was studied to verify its suitability for dose verification in advanced radiotherapy techniques. Pretreatment dose verification measurement of VMAT treatment plans was carried out using the LIC as well as small volume (0.125 cc) air-filled ionization chamber and the results were compared. The measured dose values by the two dosimeters and TPS calculated dose at a given point were found comparable suggesting that the LIC could be a good choice of dosimeter for pretreatment dose verification in advanced radiotherapy techniques.

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Nil.

Conflicts of interest

There are no conflicts of interest.

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