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Determination of the radiation dose scattered outside the target volume treated with IMRT technique

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HIGHLIGHTS

- Comparison of doses with LiF:Mg,Ti and doses calculated by the TPS.
- Irradiations have been performed in a PMMA phantom with five cavities.
- Measurements out-of-target doses in IMRT.
- Results showed a variation from 6.72 to 29.51% for out-of-target doses.
- Doses evaluated with LiF:Mg,Ti corresponding to the estimated doses given by the TPS.

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ABSTRACT

Intensity Modulated Radiation Therapy (IMRT) is an advanced mode of high precision radiation therapy that uses computer controlled linear accelerators to deliver precise radiation doses to a malignant tumor or specific areas within the tumor. This is achieved using a more precise adjustment of the beam to the three dimensional shape of the tumor by modulating or controlling the intensity of the radiation beam in multiple small volumes. IMRT also allows higher radiation doses to be focused to regions within the tumor while minimizing the dose to surrounding normal critical structures. This work aims at determining the radiation dose in two target volumes (tumors) treated at same time and the scattered dose distribution in organs at risk using thermoluminescent dosimeters of LiF:Mg,Ti for IMRT treatment technique and a polymethylmethacrylate (PMMA) phantom. The shortest distance between the cavities 1 and 2 that simulate tumors is 1.5 cm and the shortest distances from the cavity 1 to the cavities 3, 4 and 5 are, respectively, 1.9 cm, 2.2 cm and 2.65 cm. The shortest distance from the cavity 2 to cavities 3, 4 and 5 are, respectively, 5.4 cm; 5.7 cm and 1.5 cm. The relative difference for the doses measured by TLD-100 and provided by the TPS were +3.7% and −1.38%. The out-of-target doses received by cavities 3, 4 and 5 corresponded on average to 19.36, 17.84% and 6.72% of the highest dose received by the cavity 1 and the doses received by cavities 3, 4 and 5 corresponded on average to 29.51%, 27.20% and 10.24% of the dose received by cavity 2.

1. Introduction

The instrumentation and methods used to assure IMRT quality assurance procedures are not yet well established and the radiobiological consequences of IMRT treatments are not completely understood. IMRT with the use of multileaf collimators (MLCs) has the potential to achieve a much higher degree of target conformity and normal tissue sparing than most other treatment techniques, especially for target volumes or organs at risk with complex shapes (AAPM, 1983).

However, studies show that low doses of radiation can cause secondary cancers (Diallo et al., 1996; Stern, 1999; Kry et al., 2005; Harrison, 2013; Kourinou et al., 2013; Bordy et al., 2013; D'Agostino et al., 2013). The validation of phantoms and dosimetric systems are essential for obtaining a reliable and assurance quality program in radiation therapy (McNiven et al., 2004). Thus for the evaluation of

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the risks, it is necessary the use of algorithms for the calculation of out-of-field doses and the comparison with a dosimetric system is required. The overall cancer risk is influenced by the dose to several radiosensitive organs, which are distant from the radiation therapy target volume. The uncertainty in the radiosensitivity of a given organ following radiation therapy is often considerable, not least because the risk factors often used are intended for low dose radiation protection purposes (Harrison, 2013).

The appropriate selection of detectors and the determination of the detector spatial location are critical to achieve more accurate dose measurements when IMRT systems are tested and commissioned. The spatial location of measurement points must be highly accurate to enable quantitative evaluation of the calculated doses in any point. The dose read-outs should be reported for the purpose of correlating the dose with the clinical outcome. For each organ at risk it is of crucial importance to know the maximal, minimal and mean doses, the volume of the organ receiving that dose and other relevant dose-volume data. The entire dose-volume histogram (DVH) for each of the pertinent volumes (PTV, CTV and the organs at risk) must be reported.

Kourinou and collaborators (Kourinou et al., 2013) have focused on the second cancer risk after therapeutic irradiation of pediatric malignant diseases. The majority of the subsequent neoplasms appear within the primary radiation field or in a region bordering the treatment volume. Diallo and collaborators showed that 22% of subsequent neoplasms occur 5 cm away from the treatment fields. Therefore, in order to justify an exposure, both the benefits and the risks must be evaluated and compared. Whatever the difficulties and uncertainties in risk estimation, its foundation indisputably lies in the knowledge of the absorbed dose to the irradiated organs. Thus the measurement of peripheral doses, from which specific organ doses may be inferred, is a crucial pre-requisite for risk estimation.

This work aimed to determine the radiation dose distribution using LiF:Mg,Ti (TLD-100) dosimeters in five cavities of a PMMA phantom, especially designed and constructed to perform this measurements. Two cavities were considered target volumes (tumors) to be treated by IMRT technique and the other three cavities were considered organs at risk and surrounding healthy tissues. The doses calculated by the treatment planning system-TPS (isodose curves) were compared to the doses evaluated by the thermoluminescent dosimeters (TLDs).

2. Materials and methods

A batch of fifty TLD-100 dosimeters produced by Thermo Scientific previously selected with repeatability ±5% after the calibration using ^{60}Co gamma radiation were used to doses evaluation. The pre-irradiation heat treatment adopted was 1 h for 400 °C in the furnace Vulcan model 3-550 PD and 2 h for 100 °C in the surgical heater Fanem model 315-IEA 11200. The thermoluminescent responses were obtained using a reader TL Harshaw model 4500.

The dose response curve to 6 MV photons (Fig. 2) from a linear accelerator Clinac Varian 6EX was obtained using a PMMA phantom (Fig. 1) for the following absorbed doses: 0.05; 0.5; 1; 3.5 and 7 Gy corrected to the maximum dose depth by TPS "Anisotropic Analytical Algorithm (version 11.0.31)" of the Eclipse Varian.

For the dose response curve a group of ten TLD-100 wrapped in aluminium foil (dosimeters side by side) was positioned in the middle and inside of each cavity and in the top of the last PMMA plate. Each cavity was filled with PMMA plates of different thickness of 3 mm–6 mm. Each TLD-100 group was positioned in the surface of last PMMA plate getting the same height from the surface

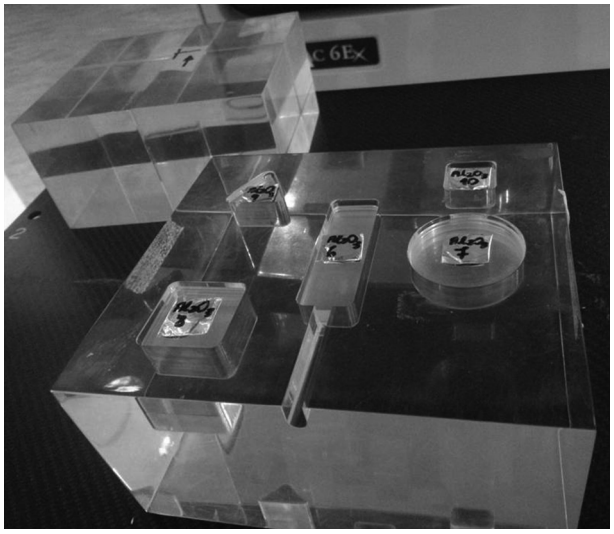


Fig. 1. PMMA phantom containing five cavities (the cavities with circular and rectangular shape were considered tumors to be treated and the other cavities of triangular and square shape (big and small) were considered organs at risk).

of the phantom. In Fig. 2 each presented value represents the average of 10 TL responses and the error bars the standard deviation of the mean (2σ) with a confidence interval of 95%.

For the dose assessments TLD-100 were separated in five group of ten dosimeters individually identified and it were irradiated with photon beams 6 MV (the procedure was the same described before for the evaluation of the dose response curve). The isocenter of the planning is located a depth of 9 cm of the PMMA phantom (considering the thickness of 8 cm of PMMA blocks). Two cavities simulate tumor volume and other cavities simulate organs at risk (Fig. 4). The irradiation planning volume of the cavities were: cavity 1 (volume = 0.8 cm^3), cavity 2 (volume = 1 cm^3), cavity 3 (volume = 0.7 cm^3), cavity 4 (volume 0.3 cm^3) and cavity 5 (volume = 0.4 cm^3). The shortest distance between the cavities 1 and 2 is 1.5 cm and the shortest distances from cavity 1 to cavities 3,

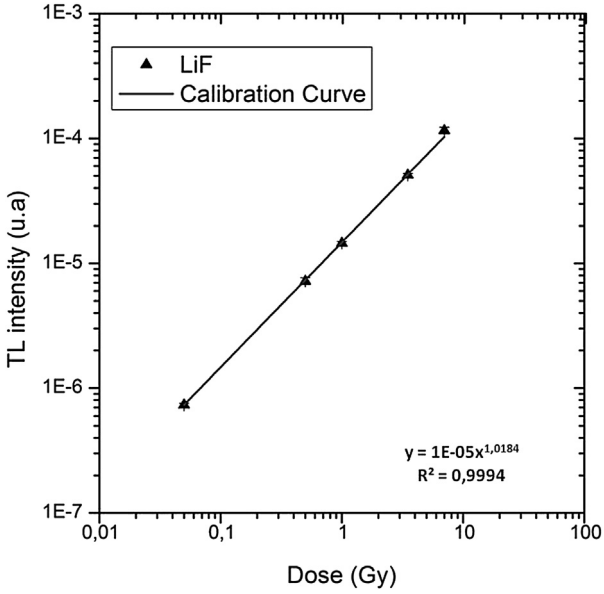
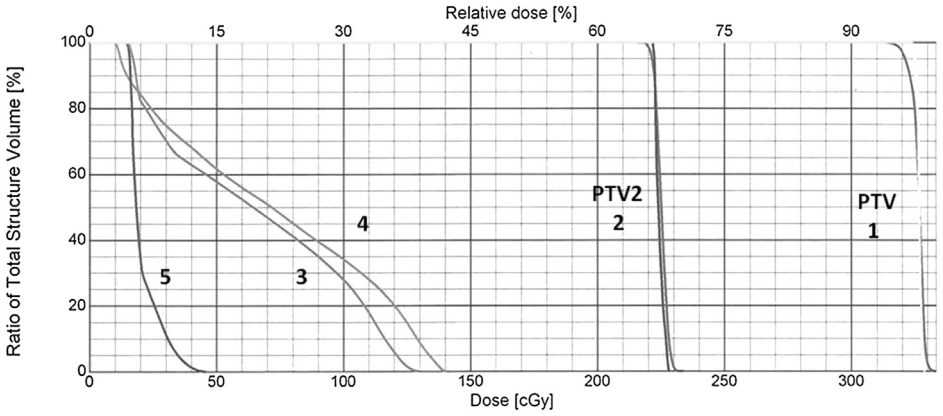


Fig. 2. TL dose–response curve for TLD-100 to 6 MV photon beam from linear accelerator Varian 6EX.



Some structures are unapproved or rejected

Structure	Structure Status	Coverage [%/%]	Volume	Min Dose	Max Dose	Mean Dose	Modal Dose	Median Dose	Std Dev
4	Unapproved	100.0 / 94.5	0.3 cm³	14.9 cGy	129.7 cGy	65.3 cGy	18.4 cGy	64.3 cGy	38.0 cGy
5	Unapproved	100.0 / 108.1	0.4 cm³	14.1 cGy	45.8 cGy	20.9 cGy	16.8 cGy	18.3 cGy	6.2 cGy
3	Unapproved	100.0 / 97.6	0.7 cm³	9.6 cGy	140.5 cGy	72.0 cGy	11.9 cGy	71.7 cGy	42.7 cGy
1	Unapproved	100.0 / 105.3	0.8 cm³	323.7 cGy	329.0 cGy	326.7 cGy	326.9 cGy	326.8 cGy	0.9 cGy
2	Unapproved	100.0 / 98.1	1.0 cm³	221.5 cGy	228.2 cGy	224.2 cGy	222.7 cGy	223.9 cGy	1.6 cGy
PTV	Approved	100.0 / 99.3	30.2 cm³	302.8 cGy	333.3 cGy	326.4 cGy	327.5 cGy	326.9 cGy	2.5 cGy
PTV2	Approved	100.0 / 100.1	34.6 cm³	203.9 cGy	233.9 cGy	225.1 cGy	225.6 cGy	225.1 cGy	2.3 cGy

Fig. 3. Cumulative dose volume histogram provided by the TPS of hospital Albert Einstein.

4 and 5 are, respectively, 1.9 cm, 2.2 cm and 2.65 cm. Regarding the cavity 2 the shortest distances for cavities 3, 4 and 5 are, respectively, 5.4 cm; 5.7 cm and 1.5 cm.

Two PMMA blocks of 8 cm thickness were positioned on the top of the phantom to ensure that the dosimeters are outside the build-up region. Before the irradiations a computed tomography was realized for each planning.

The IMRT irradiations (sliding window) were performed in the target volumes with MLCs modulated synchronously with the fluence of the radiation beam. The target volumes were treated simultaneously (cavities 1 and 2) and the scattered radiation dose distribution in the surrounding normal areas near to the tumors (cavities 3, 4 and 5) was evaluated. The TPS simulate a treatment for multiple brain metastases (cavities 1 and 2) and the other cavities may be optic chiasm, optic nerve or brainstem. The mean doses in targets were 326.7 cGy and 224.2 cGy, respectively, for the cavities 1 and 2 (Fig. 3). The IMRT irradiations were performed with seven fields and simulated one fraction of a total of ten fractions. Details about the gantry rotations, number of beam segments are related with the field number in the Table 1.

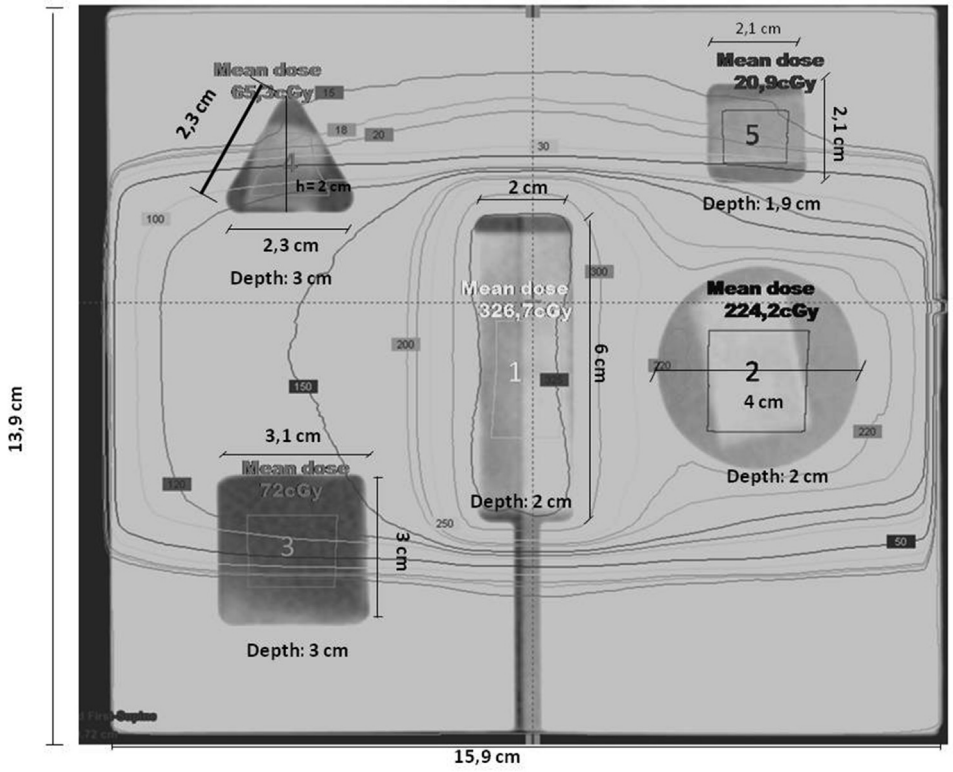


Fig. 4. Isodose curves given by the TPS showing the dose distribution in the five phantom cavities.

The obtained results were compared with the isodose curves provided by the TPS of Hospital Albert Einstein (Fig. 4). The weighting beam for all fields is 1 and the normalization point is 100% in body maximum.

3. Results and discussion

For the evaluation of repeatability from TLD-100 the IMRT irradiations were performed two times for the same conditions. Repeatability of TL response was within acceptable limits for radiation therapy purposes ranging from 3% to 4.12%.

Fig. 2 presents the TL dose–response curve for TLD-100 dosimeters to 6 MV photon beam radiation. It can be observed the linear behavior in the dose range studied, from 0.05 to 1 Gy. For doses higher than 1 Gy it can be observed a supralinear behavior from TLD-100. More points of dose are required for analyze the range of linearity of TLD-100.

Fig. 3 presents the cumulative dose volume histogram showing the mean doses calculated by the TPS related to the cavity numbers: the doses calculated by the TPS for the cavities 1 and 2 were 326.7 ± 0.9 cGy and 224.2 ± 1.6 cGy, respectively.

The isodose curves and mean doses from each cavity provided by the TPS are presented in Fig. 4.

The data provided by the TPS as the minimum (Min.), maximum (Max.) and mean doses are presented in Table 2. The doses measured by TLD-100 dosimeters in the five cavities are presented in Table 3 and summarized in Fig. 5. Fig. 5 presents a comparison of doses measured with TLD-100 and doses calculated by the TPS. Analyzing the Fig. 5 it can be noted a good agreement between doses provided by the TPS and measured by TLD-100.

The mean doses provided by the TPS ($\overline{D}_{TPS}$) and measured by TLD-100 dosimeters ($\overline{D}_{TLD100}$) and the differences (%) between both are shown in Table 4. Analyzing the data of the mean doses measured by the TLD-100 for the cavities 1 and 2 (targets) it can be noted a difference of 3.17% and −1.38%, respectively, comparing with mean doses provided by the TPS. This percentage difference is acceptable for accuracy in radiation therapy.

The mean doses measured in the cavities 1 and 2, target volumes, were 337.07 ± 13.03 cGy and 221.10 ± 6.79 cGy, respectively. The TL results agree, considering the standard deviations, with the expected by the planning system.

Regarding the doses evaluated with TLD-100 dosimeters for the cavity 3 the minimum dose was 24.90 ± 0.51 cGy, the maximum dose 99.35 ± 5.16 cGy, can be observed an intermediate isodose line of 55.75 ± 2.52 cGy and mean dose of 65.25 ± 29.85 cGy. For cavity 4 the minimum dose was 20.48 ± 2.40 cGy, the maximum dose 104.86 ± 13.27 cGy, can be observed two intermediate isodoses lines of 40.04 ± 4.12 cGy (a) and 85.22 ± 0.19 cGy (b) and mean dose 60.14 ± 35.06 cGy. For cavity 5 the minimum dose was 19.72 ± 2.37 cGy, the maximum dose 29.46 ± 2.37 cGy and mean dose 22.64 ± 5.21 cGy. In all cases the experimental results agree with the isodose curves provided by the planning system. In the case of scattered radiation the experimental doses evaluated presents standard deviations lower than the calculated.

Table 1
Information about the number of beam segments and gantry rotations according to the field number (the intensity distributions is a optimized fluence).

Field number	Gantry rotation (Varian standard)	Number of beam segments
1	330.5°	137
2	300°	97
3	261.3°	103
4	200°	120
5	171.3°	129
6	100°	126
7	70°	139

Table 2
Dose distribution provided by the TPS.

Cavity	Min. dose (cGy)	Max. dose (cGy)	Mean dose (cGy)	SD[a] (cGy)
1	323.7	329.0	326.7	0.9
2	221.5	228.2	224.2	1.6
3	9.6	140.5	72.0	42.7
4	14.9	129.7	65.3	38.0
5	14.1	45.8	20.9	6.2

[a] SD = standard deviation of the mean.

Table 3
Dose distribution measured by TLD-100 dosimeters.

Cavity	Min. Dose (cGy)± SD (cGy)	Inter. Dose[a] (cGy)± SD (cGy)	Max. Dose (cGy)± SD (cGy)	Mean Dose (cGy)	SD(cGy)
1	324.71 ± 6.29	–	346.33 ± 6.81	337.07	13.03
2	215.87 ± 1.86	–	228.07 ± 2.32	221.10	6.79
3	24.90 ± 0.51	55.75 ± 2.52	99.35 ± 5.16	65.25	29.85
4	20.48 ± 2.40	40.04 ± 4.12 (a) 85.22 ± 0.19 (b)	104.86 ± 13.27	60.14	35.06
5	19.72 ± 2.37	–	29.46 ± 2.37	22.64	5.21

[a] (a), (b) Intermediate mean doses calculated with TLD-100 in the cavity 4.

4. Conclusion

Repeatability of TL response was within acceptable limits for radiation therapy purposes ranging from 3% to 4.12%.

The doses evaluated to the tumor simulators (cavities 1 and 2) using TLD-100 corresponding to the estimated doses given by IMRT planning. The relative difference for the doses measured by TLD-100 and provided by the TPS were +3.7% and −1.38%. These results demonstrated the accuracy by TLD-100 for calculate the doses.

The scattered radiation doses received by cavities 3, 4 and 5 corresponded on average to 19.36, 17.84% and 6.72% of the highest

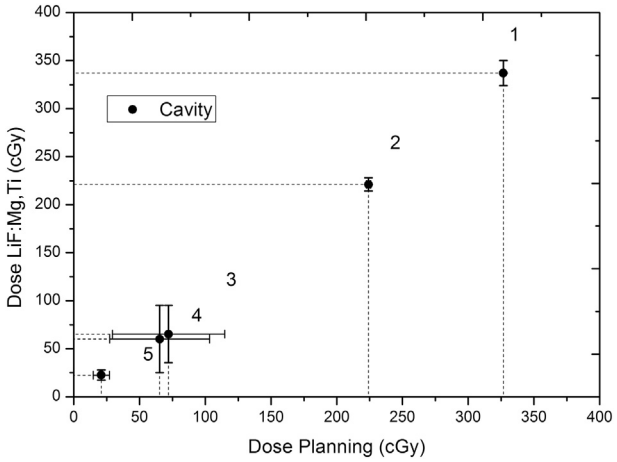


Fig. 5. Comparison of doses measured with TLD-100 and doses calculated by the TPS.

Table 4
Mean doses provided by the TPS and measured by TLD-100 dosimeters.

Cavity	$\overline{D}_{TPS}$ (cGy) ± SD (cGy)	$\overline{D}_{TLD100}$(cGy) ± SD (cGy)	Difference (%)$\frac{\overline{D}_{TLD100}}{\overline{D}_{TPS}}$
1	326.7 ± 0.9	337.07 ± 13.03	3.17
2	224.2 ± 1.6	221.10 ± 6.79	−1.38
3	72.0 ± 42.7	65.25 ± 29.85	−9.38
4	65.3 ± 38.0	60.14 ± 35.06	−7.90
5	20.9 ± 6.2	22.64 ± 5.21	8.33

dose received by the cavity 1. The doses received by cavities 3, 4 and 5 corresponded on average to 29.51%, 27.20% and 10.24% of the dose received by cavity 2. The measure of out-of-target doses at around 11.25 cm can vary up to 55%. The results measured by TLD-100 agreed with the out-of-target doses provided by the TPS.

This study can contribute to an accurate mapping of the doses received at any point in the PMMA phantom and further studies will analyze the isodose curves according to the delimitation of its areas. Therefore the evaluation of the IMRT technique with the use of dosimetric methods can be used for assuring the quality control for the absorbed doses in whole planning.

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