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Phantom development and implementation for Gamma Knife® dosimetry

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Stereotactic radiosurgery is a procedure that primarily treats intracranial lesions to destroy tumour cells that are inaccessible surgically. Gamma Knife® is a stereotactic radiosurgery unit that can treat brain lesions using ^{60}Co beams, non-invasively. Fields from Gamma Knife® helmets are considered small, therefore, in order to ensure accurate dosimetry, detectors for dose measurements have to be carefully chosen. The IAEA TRS 483 code of practice is a standardized guide for dosimetric procedures and indication of detectors for reference dosimetry of small fields used in radiotherapy beams. The objective of this work was to assess the implementation of the TRS 483 recommendations for Gamma Knife® dosimetry, using two micro-ionization chambers, *Exradin* A16 and PTW Pinpoint 3D 31016. An acrylic phantom with the same dimensions as those provided by Elekta, Gamma Knife's manufacturer, was built as an alternative. The phantom was characterized for its implementation for Gamma Knife® dosimetry and to be used as part of an audit kit by a Secondary Standard Dosimetry Laboratory (SSDL) in Brazil. Alanine pellets were used as reference detector. Dosimetry results for the acrylic phantom were compared with the ones obtained in phantoms specified by Elekta, which are made of Acrylonitrile Butadiene Styrene (ABS) and Solid Water materials. TRS 483 recommended correction factors were used to calculate the absorbed dose to the water taking into consideration the phantom material. Absorbed dose measurements performed using the designed acrylic phantom showed results comparable to the ones obtained with commercially available phantoms. The new phantom is suitable for Gamma Knife reference and relative dosimetry. The results of this work aim to contribute to the implementation of the TRS 483, mainly in the area of Gamma Knife dosimetry and the use of small volume ionization chambers.

1. Introduction

Stereotactic radiosurgery is a procedure that primarily treats intracranial lesions to destroy tumour cells that are inaccessible surgically. Gamma Knife® is a stereotactic radiosurgery unit that can treat brain lesions using ^{60}Co beams, non-invasively.

In Gamma Knife® units it is not possible to achieve reference conditions, in terms of field-size and source to detector distance (SDD). This can reduce the accuracy required for clinical dosimetry in radiotherapy and its traceability to reference dosimetry, based on Codes of Practice (Andreo et al., 2000; Almond et al., 1999; McEwen et al., 2014; AAPM, 1983; Benmakhlouf et al., 2015).

The International Atomic Energy Agency (IAEA) and the American Association of Physicists in Medicine (AAPM) have recently published the Technical Reports Series (TRS) 483. The document aims to standardize methods and procedures for the dosimetry of small static fields used in external beam radiotherapy (IAEA-AAPM 2017; Palmans et al. 2018).

The SSDL located in Sao Paulo, Brazil, is aiming to introduce end-to-end audits that are clinically relevant, specifically for stereotactic radiosurgery with Gamma Knife® machines.

In order to achieve that, an acrylic phantom was designed and built for Gamma Knife® dosimetry including bespoke inserts for small volume ionization chambers, Exradin A16 and PTW 31016, and as part of the audit kit and a procedure where the ionization chambers are directly calibrated against a secondary standard at the SSDL (Costa 2018).

The use of acrylic phantoms represents an affordable alternative to more expensive phantom materials (Gopishankar et al. 2013; Zhu et al. 2010).

This work also aims to contribute to the implementation of the

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protocol in the area of Gamma Knife® dosimetry and it has followed the recommendations from TRS 483 for Gamma Knife® dosimetry using ionization chambers suggested by the protocol and applying correction factors for the use of different phantom materials.

2. Materials and methods

The construction and design of the acrylic phantom was followed by geometrical and dosimetric tests on Gamma Knife®. Those tests aimed to investigate the effects of cost and time required to build a prototype, as well as the influence of phantom geometry, type of material and density for the accuracy of absolute and relative dosimetry. Acrylic was chosen because of its lower cost, density relatively close to water, possibility for quick production and robustness (easy handling). The design was based on the ABS phantom, developed by the Gamma Knife® manufacturer, Elekta. That allowed the use of the same adaptor to position the phantom as the one used for the ABS phantom.

The phantom sphere was made by a company specialized in acrylic materials (Acriresinas, Sao Paulo, Brazil). The design was completed by drilling the phantom to a shape for a detector insert. Computerized machining for inserts (for two different small volume ionization chambers) was performed at National Physical Laboratory (NPL) workshop. A third insert for the insertion of alanine pellets was also designed. Each insert was drilled according to the size of the detector: ionization chambers Exradin A16 and PTW Pinpoint 31016 and 2.5 mm alanine pellets (with space for three pellets). Once inside the phantom, the sensitive volume of the ionization chambers and the middle alanine pellet are centrally located in the phantom.

Considering the small size of the reference field (16 mm Ø), and that the position and size of the detector can significantly change the dosimetry results, it was clear that the construction and design of the combination phantom/inserts would have to be performed meticulously.

The design was verified with Linac cone beam CT scans for the phantoms and the different inserts.

Besides the micro-chambers already mentioned, a PTW Semiflex 31010 was also used. An NPL's secondary standard, NE2611 chamber, was used to calibrate the PTW Pinpoint 31016 and the Exradin A16 in terms of absorbed dose to water in a reference Co^{60} beam at NPL.

The dosimetric system formed by the acrylic phantom + insert + small volume detector was tested in the Gamma Knife® Perfexion at Queen Square Radiosurgery Centre (QSRC, London, UK). QSRC uses the Solid Water phantom and a PTW Semiflex 31010 ionization chamber for reference dosimetry and routine quality assurance. In order to assess the feasibility of the use of the acrylic designed phantom, seven different measurement setups were used: both phantoms (ABS and acrylic) were used and compared. The setups were:

Setup 1: Solid Water phantom and PTW Semiflex 31010
Setup 2: Solid Water phantom and Exradin A16
Setup 3: Solid Water phantom and PTW Pinpoint 31016
Setup 4: Acrylic phantom and Exradin A16
Setup 5: Acrylic phantom and PTW Pinpoint 31016
Setup 6: Solid Water phantom and 2.5 mm alanine pellets
Setup 7: Acrylic phantom and 2.5 mm alanine pellets.

For each of the combinations phantom-chamber, the same positioning procedure was followed. A prescription with a large irradiation time was delivered for each measurement, allowing for the collection of charge for 10 independent 1 min readings on the time of the electrometer. All measured dose rates were compared with the Gamma Plan dose rate which is the value used for calculations of treatment time in the Gamma Knife® software. Equation (1) was used to calculate the dose rate of the Gamma Knife® (Alfonso et al. 2008).

Table 1
$k_{Q_{msr}}^{f_{msr},f_{ref}}$ correction factors for Gamma Knife® Perfexion.

Ionization Chamber	Gamma Knife® Perfexion $f_{msr=16\,mm}$		
	Solid Water®	ABS	Water
PTW Pinpoint 31016	1.0040	1.0110	0.9991
Exradin A16	1.0167	1.0295	1.0127
PTW Semiflex 31010	1.0037	1.0146	1.0001

$$D_{w,Q_{msr}}^{f_{msr}} = M_{Q_{msr}}^{f_{msr}} N_{D,w,Q_0}^{f_{ref}} k_{Q_{msr},Q_0}^{f_{msr},f_{ref}} \quad (1)$$

where: $M_{Q_{msr}}^{f_{msr}}$ are the chamber readings (corrected for all the influence quantities: temperature, pressure, polarity and ion recombination) in the reference beam for Gamma Knife® Perfexion (16 mm Ø); $N_{D,w,Q_0}^{f_{ref}}$ is the calibration coefficient factor in terms of absorbed dose to water in the quality and field size of reference for the calibration laboratory; $k_{Q_{msr},Q_0}^{f_{msr},f_{ref}}$ is the beam quality correction factor for the use of the calibration coefficient in the 16 mm Ø field (reference beam for Gamma Knife® Perfexion).

The factor is close to unity for most chambers suitable for reference dosimetry in Gamma Knife® machines if the calibration is performed in water. However for this work, the dosimetry was performed in acrylic and Solid Water phantoms therefore the correction factors have to include the conversion to absorbed dose to water. TRS 483 (IAEA-AAPM 2017) provides the $k_{Q_{msr},Q_0}^{f_{msr},f_{ref}}$ for the Gamma Knife® Perfexion, which are summarized in Table 1, for the ionization chambers used in this work.

The phantom designed and presented in this work was made of acrylic. Thus, a correction factor $k_{Q_{msr}}^{w,\,plastic}$, as presented by Mirzakhanian et al. (2018), in Equation (2), was also considered to calculate the dose rate:

$$k_{Q_{msr}}^{w,\,acrilic} = K_q'[(\rho_e^{rel} - 1)b + 1] \quad (2)$$

where: K_q' is the correction factor for each ionization chamber, measured on Monte Carlo calculations; ρ_e^{rel} is the relative density of acrylic and b is 0.4285 ± 2.5%.

Alanine pellets (2.5 mm Ø) produced and analysed at NPL (Sharpe and Sephton 2015) were considered as a reference detector for this work. Three pellets were used for each measurement. At the time of the experiments, 20-min irradiations were needed so that the pellets would receive more than 30 Gy, which is the minimum dose required for adequate levels of noise and frequency distortion for this pellets size.

To validate the use of the Acrylic phantom with quality assurance (QA) purposes, output factors relative to the 16 mm Ø collimator were also measured and compared with the default values in the Leksell Gamma Plan® treatment planning system (0.9 for the 8 mm collimator and 0.814 for the 4 mm collimator). Using the formalism introduced by the TRS 483 (IAEA-AAPM 2017), Equation (3) was used to calculate relative output factors.

$$\Omega_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}} = \frac{M_{Q_{clin}}^{f_{clin}}}{M_{Q_{msr}}^{f_{msr}}} k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}} \quad (3)$$

where: $M_{Q_{clin}}^{f_{clin}}$ and $M_{Q_{msr}}^{f_{msr}}$ are detector readings (corrected for atmospheric conditions) for a clinical (non-reference conditions) beam and the machine specific reference field (msr 16 mm Ø collimator), respectively.

3. Results and discussion

The acrylic phantom and its inserts for three different detectors are shown in Fig. 1.

Fig. 2 shows the acrylic phantom positioned for measurements on the Gamma Knife® Perfexion machine.

Table 2 shows the results for the dose rate measured following the

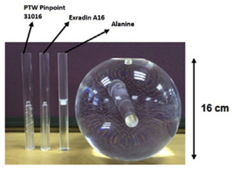

Fig. 1. Purposely designed acrylic phantom for Gamma Knife® dosimetry and QA.

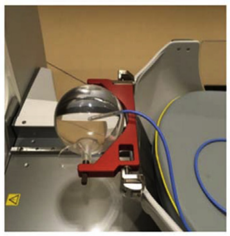

Fig. 2. Acrylic phantom positioned with Elekta's ABS phantom adaptor in the Gamma Knife®.

Table 2
Gamma Knife® dosimetry using Solid Water® phantom and PTW Semiflex 31010.

Setup 1 Gamma Plan dose rate (Gy/min): 1.859	
$N_{D,w}$ (Gy/nC)	0.301
Collected charge (nC)	6.077
$k_{t,p}$	1.016
Dose rate (Gy/min)	1.883 ± 3.0%

procedures for Setup 1 as used at the Queen Square Radiosurgery Centre: Solid Water phantom and PTW Semiflex 31010. In this case, chamber readings were only corrected by atmospheric quantities of influence ($k_{t,p}$). The difference between measured and Gamma Plan dose rate was 1.28%.

Table 3 shows the dose rate measured for Setup 2: Solid Water phantom and Exradin A16. The following correction factors were considered for the dose rate calculation: $k_{t,p}$, ion recombination (k_{ion}), polarity (k_{pol}), $k_{Qmsr}^{fmsr,fref}$ for the Exradin A16, (as per in Table 1). The difference between the dose rate measured and the Gamma Plan dose rate was 2.28%.

Table 4 shows the dose rate measured for Setup 3: Solid Water phantom and PTW Pinpoint 31016. Same correction factors as in Setup 2 were considered. The difference between the dose rate measured and the Gamma Plan dose rate was 1.86%.

Table 5 shows the dose rate measured for Setup 4: Acrylic phantom and Exradin A16. Besides the factors already mentioned as per in Setups 2 and 3, a correction for the phantom material $k_{Qmsr}^{w,acrilic}$ was also considered. In this case, the difference between the dose rate measured and Gamma Plan dose rate was 3.35%.

Table 6 shows the dose rate for Setup 5: Acrylic phantom and PTW

Table 3
Gamma Knife® dosimetry using Solid Water® phantom and Exradin A16.

Setup 2 Gamma Plan dose rate (Gy/min): 1.892	
$N_{D,w}$ (Gy/nC)	4.161
Collected charge (nC)	0.455
$k_{t,p}$	1.016
$k_{Qmsr}^{fmsr,fref}$	1.017
k_{ion}	0.999
k_{pol}	0.997
Dose rate (Gy/min)	1.936 ± 2.3%

Table 4
Gamma Knife® dosimetry using Solid Water® phantom and PTW Pinpoint 31016.

Setup 3 Gamma Plan dose rate (Gy/min): 1.892	
$N_{D,w}$ (Gy/nC)	2.546
Collected charge (nC)	0.751
$k_{t,p}$	1.011
$k_{Qmsr}^{fmsr,fref}$	1.004
k_{ion}	0.999
k_{pol}	0.994
Dose rate (Gy/min)	1.928 ± 1.7%

Table 5
Gamma Knife® dosimetry using Acrylic phantom and Exradin A16.

Setup 4 Gamma Plan dose rate (Gy/min): 1.859	
$N_{D,w}$ (Gy/nC)	4.161
Collected charge (nC)	0.418
$k_{t,p}$	1.024
$k_{Qmsr}^{fmsr,fref}$	1.084
k_{ion}	0.999
k_{pol}	0.997
Dose rate (Gy/min)	1.924 ± 2.7%

Table 6
Gamma Knife® dosimetry using Acrylic phantom and PTW Pinpoint 31016.

Setup 5 Gamma Plan dose rate (Gy/min): 1.859	
$N_{D,w}$ (Gy/nC)	2.546
Collected charge (nC)	0.690
$k_{t,p}$	1.019
$k_{Qmsr}^{fmsr,fref}$	1.072
k_{ion}	0.999
k_{pol}	0.994
Dose rate (Gy/min)	1.908 ± 2.2%

Table 7
Gamma Knife® dosimetry using the Solid Water and acrylic phantoms and 2.5 mm alanine pellets. Irradiation time: 20 min.

Setups 6 and 7 Alanine Pellets (Gy)	Solid Water® and alanine pellets	Acrylic and alanine pellets
Pellet 1	37.165 ± 3.2%	37.745 ± 3.6%
Pellet 2	36.480 ± 3.2%	37.656 ± 3.5%
Pellet 3	35.523 ± 3.2%	37.741 ± 3.5%
Average	36.389 ± 4.0%	37.714 ± 3.9%
Gamma Plan difference (%)	1.9	1.4

Pinpoint 31016. Same correction factors as per in Setup 4 were considered. The difference between the dose rate measured and the Gamma Plan dose rate was 2.59%.

Table 7 shows detailed results for dose measurements with alanine pellets using both phantoms (ABS and acrylic). For the acrylic phantom, the correction factor $k_{Qmsr}^{w,acrilic}$ was considered for the dose calculation.

For the Solid Water phantom, the average dose for the three pellets was 36.39 Gy. The difference between the Gamma Plan calculated dose and the averaged alanine measurement was 1.9%.

For the acrylic phantom, the average dose for the three pellets was 37.71 Gy. The difference between the Gamma Plan calculated dose and the alanine measurement was 1.4%.

The CT scans of the phantoms with the alanine inserts showed a slight misalignment in the position of the central pellet in relation to the

Table 8
Dose rate measurements. Percentage difference for all setups and the acrylic phantom + alanine as reference.

Setup	Dose rate (Gy/min)	Gamma Plan difference (%)	Difference (%) Reference (Acrylic phantom + Alanine)
Solid Water® + Semiflex	1.883	1.28	0.10
Solid Water® + Exradin	1.936	2.28	2.63
Solid Water® + Pinpoint	1.928	1.86	2.23
Acrylic + Exradin	1.924	3.35	2.02
Acrylic + Pinpoint	1.908	2.59	1.20
Solid Water® + Alanine	1.819	1.90	3.62

Table 9
Output factor measured for all setups.

Setup	Collimator			
	16 mm	8 mm	4 mm	Uncer-tainty
Solid Water® + Semiflex	1	0.734	0.328	± 3.5%
Solid Water® + Exradin	1	0.887	0.812	± 2.9%
Solid Water® + Pinpoint	1	0.893	0.817	± 2.5%
Acrylic + Exradin	1	0.904	0.689	± 3.2%
Acrylic + Pinpoint	1	0.871	0.637	± 2.9%
Solid Water® + Alanine	1	0.890	0.726	± 3.7%
Acrylic + Alanine	1	0.889	0.631	± 4.0%

Table 10
Percentage difference between output factors measured and Monte Carlo calculated.

Setup	Collimator	
	8 mm	4 mm
Solid Water® + Semiflex	18.37%	60.02%
Solid Water® + Exradin	1.37%	0.19%
Solid Water® + Pinpoint	0.71%	0.46%
Acrylic + Exradin	0.44%	15.23%
Acrylic + Pinpoint	3.21%	21.63%
Solid Water® + Alanine	1.04%	10.81%
Acrylic + Alanine	1.21%	22.48%

position of the measurement point for the ionization chambers. As a result of that, a higher dose was delivered to the first pellet, instead of the central one.

The misalignment of the position of the effective point of measurement of the detectors (in the inserts) in relation to the center of the phantom (isocenter of the Gamma Knife) could be a limitation to achieve lower uncertainties in the measurement of output factors for the smaller Gamma Knife collimators (8 mm and 4 mm) for Gamma Knife users without imaging system.

Table 8 shows the percentage difference between the measurements with all the configurations used against the Gamma Plan and against the phantom proposed by this work with the detector considered as reference: alanine (acrylic phantom + alanine pellets).

For all setups, differences between the measured dose rate and the one calculated by Gamma Plan were not larger than 3.4%. Similarly, the differences between the measured dose rate for the acrylic phantom with alanine pellets were not larger than 3.7%. The latest results were a consequence of the inserts for alanine pellets for both phantoms not being perfectly built.

Table 9 shows the results for the relative output factors calculated using equation (3) and for all the setups investigated in this study.

Table 10 shows the percentage differences with Gamma Plan default relative output factors (golden data, calculated by Monte Carlo).

For the Solid Water phantom and both micro ionization chambers, calibrated at NPL, the differences with the golden data are smaller than 1.5% for both collimators. The results with alanine for the same phantom and the smaller collimator were larger than expected and similar happened for the acrylic phantom. In both cases that is a reflection of the misalignment of the position of the central pellet within the centre of the phantom.

Similarly, very large differences for the micro chambers in the acrylic phantom and for the smaller collimator would imply that the design of the inserts needs to be perfected if the system is going to be used for QA measurements involving the smaller collimators.

The larger differences for the measurements with the Semiflex 31010 chamber were expected as the chamber is large for the size of the fields.

4. Conclusion

The newly published TRS 483 provides a standard guide for small field dosimetry in radiotherapy, and introduces a formalism that recommends the use of small volume ionization chambers that have been calibrated in terms of absorbed dose to water at a standard dosimetry laboratory. TRS 483 also emphasizes that the perfect detector for small field measurements does not exist and that to determine output factors and lateral beam profiles, two or more detectors should be used so the results can deliver more confidence and the user can minimize dosimetric errors. This work aimed to design and build a new acrylic phantom for Gamma Knife® dosimetry with its geometry close to the phantoms provided by Elekta. Acrylic is a less expensive material and such a phantom, once properly validated, could be used by organizations responsible for auditing Gamma Knife® centres, in countries where the institutions in charge of verifications have less resources. The phantom with the proper small detectors (calibrated in terms of absorbed dose to water in reference conditions) and the application of the TRS 483 formalism, form a suitable verification system. This work also showed that besides ionization chambers, small alanine pellets (2.5 cm Ø) can be used as a reference dosimeter. The dosimetric measurements using the new acrylic phantom have shown results close to the ones obtained with existing phantoms for Gamma Knife® dosimetry. All correction factors referred at TRS 483 have been considered for the dose calculations performed in this work.

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