Experimental validation of TG-43 brachytherapy dose calculation formalism for High Dose Rate Cobalt-60 brachytherapy source

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Abstract

Background: The present study aims to develop a method of in-phantom dosimetry around HDR brachytherapy Co-60 photon source. The present work of in-phantom dose measurement was designed to experimentally analyze or verify the brachytherapy dose calculation methodology recommended by the AAPM TG-43 report. This can also be considered as an experimental validation of TG-43 consensus data.

Materials and Methods: At first, the radial profiles with respect to radial distance were obtained in water by the ionization chambers and solid-state detectors under AAPM TG-43 reference conditions. Secondly, these experimentally obtained radial profiles were used to calculate radial function as per the AAPM TG-43 formulation and compared with AAPM-TG 43 consensus data.

Results: In the present study, it was observed that due to a very sharp gradient of dose rate along radial distances the AAPM TG-43 reference point i.e. 1 cm from the source axis was very sensitive to radial distances and cannot be considered very suitable for analyzing the data. So to outer number any chance of error or misinterpretation, for this study, the data was analyzed for two reference points i.e. 1 cm and 4 cm. Present work also explored the applicability of various detectors for experimental HDR brachytherapy dosimetry and the role of Effective Point of Measurement (EPOM) and volume averaging in detector responses in HDR Co-60 dosimetry. It was observed that the individual properties or character of each detector was more crucial for accurate measurements instead of the type of detector.

Conclusion: Both the categories of the detector, solid-state and ionization chambers have several suitable detector options for HDR brachytherapy dosimetry, especially for Co-60 source. Micro diamond in, solid-state detector and Semiflex chambers (small volume) in ionization chamber detector categories were found suitable for HDR brachytherapy experimental dosimetry.

KEYWORDS: Brachytherapy, Cobalt-60, In-phantom measurement

1. INTRODUCTION:

High Dose Rate (HDR) brachytherapy is an essential part of radiotherapy for cancer management. The combination of brachytherapy and external radiotherapy has shown better clinical outcomes in comparison to external beam therapy alone in localized cancer management [1, 2]. Experimental dosimetry is quite new to HDR brachytherapy especially, in-phantom water measurements due to various technical reasons. Currently, dosimetry in HDR brachytherapy is limited to measurement of air-kerma strength of the brachytherapy source with the help of well-type ionization chamber and to calculate the absorbed dose rate to water as per the recommendations of the AAPM TG-43 [3]. This standard method worked very well to serve the immediate needs of brachytherapy dosimetry. However, with the introduction of complex procedures with the increasing scope of HDR brachytherapy treatments and new dose calculation algorithm, the experimental dosimetry should be exploited to find or understand these complexities. This is a must requirement for a more realistic assessment of radiation doses to risk organs in given clinical situations. Experimental dosimetry with water phantom may provide a better understanding of the radiation dose profile around the HDR brachytherapy source. There are various challenges in experimental dosimetry with brachytherapy sources. These arise mainly because of the high gradient of the photon fluence as a function of radial distance from the source centre. In addition to this, the geometric function of the brachytherapy sources is also very sensitive to radial distance, which makes any measurement in water phantom highly sensitive to positional accuracy [4].

Recently, there were few attempts of experimental dosimetry for HDR brachytherapy sources. Most of these involve Ir-192 brachytherapy source [5-7]. In spite of these few studies, a universally acceptable design of experimental dosimetry for HDR Brachytherapy sources has not been evolved due to the large scope of uncertainty in measurements. There is an urgent need for experimental design to address these challenges of experimental dosimetry for Co-60 HDR brachytherapy source. The present study has been planned to analyze the challenges and design a method of experimental dosimetry in HDR remote afterloading brachytherapy with Cobalt-60 source. Measurements are designed to study radial dose function for Co-60 HDR brachytherapy source. The present work is inspired by Schoenfeld *et al* work with Iridium-192 brachytherapy source [5]. They have worked on reference condition for experimental dosimetry with Ir-192 brachytherapy source to find absorbed dose to water.

Ionization chambers are considered the gold standard in clinical radiation experimental dosimetry. They are also widely available with radiotherapy departments. For HDR brachytherapy, with the geometrical point of view and need of positional accuracy, the dosimetric detectors with high spatial resolution appear as the method of choice. Solid-state detectors seem best with spatial resolution. Because of these reasons both the type of detectors i.e. solid state and ionization chambers were employed in this study. The included detectors, three types of ionization chamber and two types of the solid-state detector with different sizes and geometry were used for the measurement.

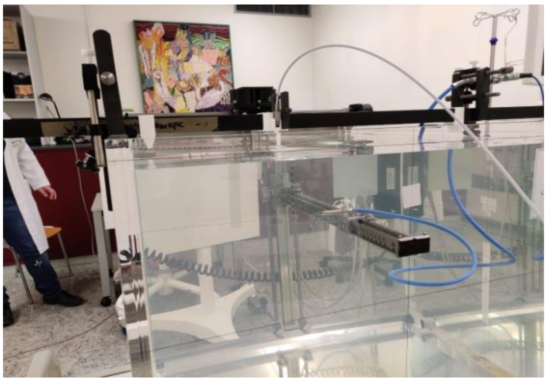
AAPM TG-43 recommended reference point for the dose rate calculations i.e. 1 cm from the source axis, does not appear suitable as the reference point for analyzing the experimental data as it is very sensitive to positional accuracy. Geometric function is also quite sensitive to positional accuracy, this has a huge impact on the calculation of radial function. Because of these facts, 80 mm from the source centre have been chosen for in-phantom dose measurements (Krieger phantom) [8]. Long before this, Quast and Bormann had proposed a cross-calibration distance from the source centre of 40 mm [9]. In the present study, two reference points were chosen i.e. $r = 1$ cm, 4 cm from the source axis to analyze the data effectively and rule out uncertainty due to positional accuracy. Present work also explored the applicability of various detectors for experimental HDR brachytherapy dosimetry and the role of effective point of measurement (EPOM) and volume averaging in detector responses in HDR Co-60 dosimetry.

2. MATERIALS AND METHODS

2.1 Experimental setup

All measurements were planned in an MP3-M water phantom (PTW, Wurzburg, Germany) with outer water tank dimensions 636 mm × 636 mm × 523 mm. All the measurements were performed in distilled water. The phantom size was appropriate to provide full scatter conditions up to 10cm of radial distances [3,10,11]. A heavy density rectangular rod was used across the phantom with in-house 3D printed needle holder. This holds the metallic needle in the middle of the water tank as shown in Fig. 1.The applicator was a simple geometry of straight steel needle. Bebig SagiNova, Eckert & Ziegler, Germany HDR remote afterloading machine with Co-60 source was employed to perform all the measurements.

Figure 1: The experimental setup includes water phantom with heavy density rectangular rod across the phantom with in-house 3D printed needle holder. Applicator was straight steel needle with source access.



2.2 Localization of the source Centre and determination of EPOM

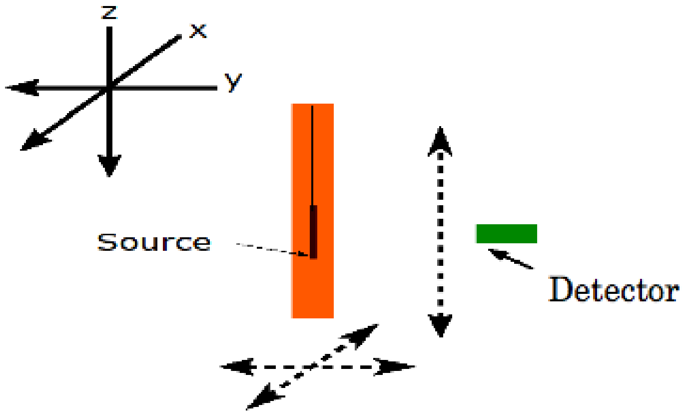
The dose gradient of HDR brachytherapy sources was very high; a minor uncertainty in the positioning of detector placement can contribute to large errors in measurements. To overrule these uncertainties accurate localization of the source centre was very important for accurate and precise measurements. As the brachytherapy sources also show characteristics of inverse square law ($1/r^2$) with radial distance, this is included in the definition of the geometric function. The behavior of photon fluence in a water phantom surrounding the photon source is a parameter of key importance in the positioning of the detector around the source.

The MP3-M water phantom features a step precision of 0.1 ± 0.03 mm [12]. Commercially, this system was designed for external beam measurements. The system has centre check system to self locate the centre of beam, however this system was not very useful for our measurement as the type of radiation beam in external beam therapy is quite different from brachytherapy isotropic dose distribution. In this study, a new method of source localization was designed, which fits the requirement of this experimental setup and source type.

A method for localization of the source centre by accessing all three axes of the source was designed with a single detector. The MP3-M MEPHPYSTO mc^2 (PTW-Freiburg, Germany) Software and the OriginPro software (OriginLab Corporation, USA) was used for localization of the centre of the source. It was a three-step process, as shown in Fig. 2 below.

1) First manually setting the detector at the approximate centre of the needle tip underneath the needle, with its symmetry axis adjusted parallel to the symmetry axis of the needle.
2) Second, the detector takes the Percentage depth dose (PDD) profile along the longitudinal axis of the source.
3) Third, Inline and cross-line profile was acquired underneath the source.

Figure 2: Three step process of source localization with single detector.



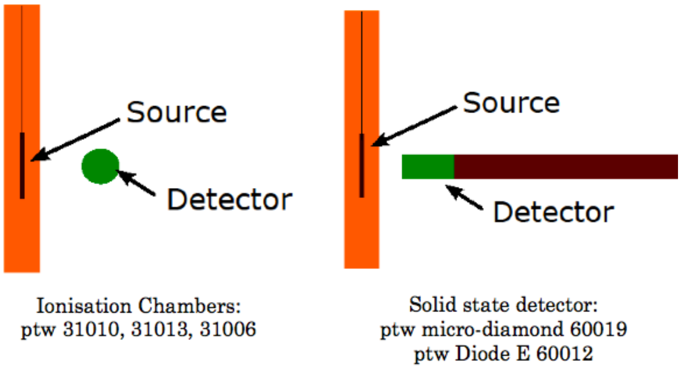
This localization scans by single detector was designed with scanning software. This provides radiation dose profiles in all the three dimensions of the source. These profiles were analyzed with the help of Origin software using Gaussian fitting and obtained coordinates of source centre were used as the origin for further measurements. The HDR brachytherapy system allows only a maximum of 40 minutes source on time for single measurement process. In case the measurements required more than 40 minutes of source on time then source was drawn back to the machine and brought again for another source on time. Schoenfeld *et al* have reported that there can be an inaccuracy of order of 1.5 mm with consecutive source beam on time [5]. As the measurements were observed to be very sensitive to positional accuracy, the inaccuracy of this magnitude may induce large error to the measurements. To rule out any errors during measurements due to this uncertainty of source center position between two consecutive sources applications, the source localization process needs to be repeated for every measurement process. For this study, source axis localization was performed for every source application.

The localization scans were performed with the respective detectors for every acquisition of radial profile. The source centre localization procedure was performed at the beginning of each set of in-phantom dose measurements. EPOM determination was planned with iterative approach. A random set of suitable EPOM corrections was applied. The corrected data was compared with reference data and analyzed for their closeness. Iteratively best-resulted corrections were considered as the EPOM for the respective detectors.

2.3 Radial profile acquisition

After localization scan and measurement origin identification, the detector was employed to acquire radial profiles. In the present study, five detectors were used, which include three ionization chambers and two solid-state detectors. They were 0.3 cm^3 Semiflex chamber PTW 31013, 0.125 cm^3 Semiflex chamber PTW 31010, Pinpoint PTW 31006, micro diamond PTW 60019 and Dosimetry Diode E PTW 60012. All detectors were from PTW, Freiburg, Germany. Two different orientations of detectors were used as shown in Fig. 3 to deal with the volume averaging effect in ionization chambers and to have maximum efficiency in solid-state detectors.

Figure 3: Detector orientation for acquisition of radial dose profile.



It was assumed that source geometry was symmetric and had isotropic dose distribution. The radial dose profile acquisitions were planned to direct in an outward direction ranging over radial distances from 6 mm to 150 mm. The electrometer integration times per point of measurement were chosen as 5 or 15 seconds depending upon the type of the detector. For every detector, a set of three radial signal profiles were acquired to ensure the reproducibility of data. For each set, the source centre localization was repeated.

3. RESULTS AND DISCUSSION

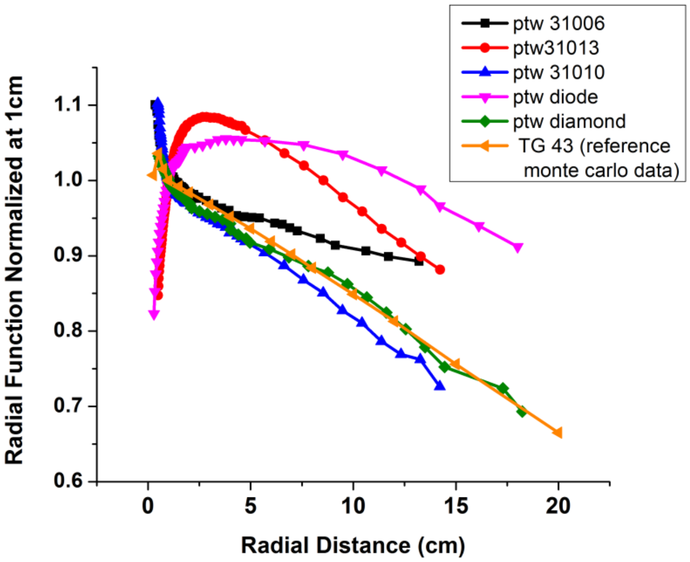
For every detector, the three consecutive measurements of radial dose profiles $M(r)$ were analyzed for standard deviations and reproducibility. For every measurement, the fluctuation was observed in the source position however the acquired data was quite reproducible. The acquired radial dose profiles were analyzed logarithmically. The profiles were found reproducible within 0.5% of each other for the 0.3 cm^3 Semiflex chamber (PTW 31013), 0.125 cm^3 Semiflex chamber (PTW 31010) and Dosimetry Diode E (PTW 60012) for the whole range of measurements. The pinpoint ionization chamber (PTW 31006) was found reproducible within 0.6% up to 80 mm of radial distance and after this reproducibility was within 2.3% of other consecutive measurements. The micro diamond detector

(PTW 60019) was found reproducible within 0.5% up to 120 mm of radial distance and after this reproducibility was within 1.1% of other consecutive measurements.

An iterative method of analysis was employed to find the effective point of measurement (EPOM) for different detectors with reference to TG-43 data. The evaluated EPOM's were in the range of -0.2 mm to 0.5 mm for all three ionization chambers. This range of corrections cannot be considered as an EPOM correction for the detectors as the magnitude of these corrections were very small. Therefore, these corrections can be considered as an error in detector placements or positioning. These corrections of feeble magnitude for ionization chambers can be attributed to choice of detector orientation or to high energy of gamma photon of Co-60. Schoenfeld *et al* reported the EPOM correction of order of a centimeter with a different orientation of ionization chambers for Ir-192 source. The present study recommends the use of the same orientation for ionization chambers to avoid the significant EPOM correction in HDR brachytherapy experimental dosimetry for Co-60. Present study also evaluated the volume averaging effect for ionization chamber with different volumes. The volume averaging corrections for the ionization chambers of such small volumes were sufficiently close to unity at larger radial distances (>3 cm).

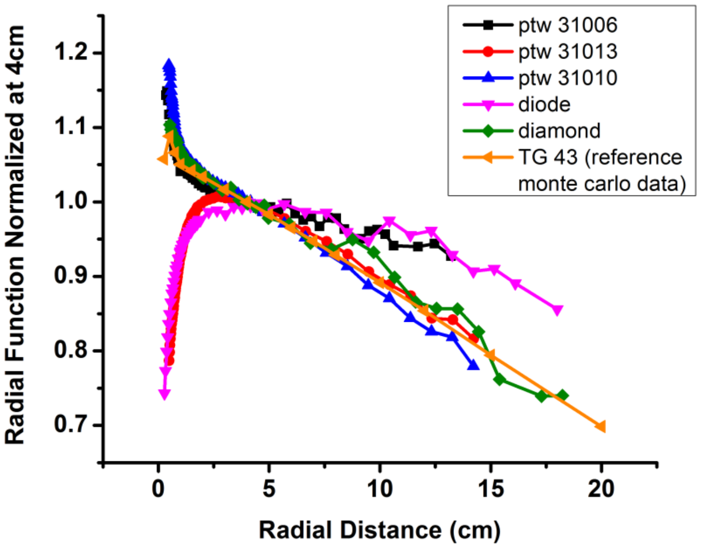
Radial dose functions were calculated according to the AAPM TG-43 report for every detector. The acquired radial functions were analyzed for the two chosen references points i.e. 1 cm and 4 cm and compared with AAPM TG-43 consensus data for both the reference points. Fig. 4 illustrates the graphical analysis of radial functions for all the detectors compared to AAPM TG-43 consensus data for the reference point 1 cm. It was observed that this point of reference is not ideal for analysis. The 0.3 cm^3 Semiflex ionization chamber (PTW 31013), 0.125 cm^3 Semiflex ionization chamber (PTW 31010) and micro-diamond (PTW 60019) had shown comparative behavior to AAPM TG 43 consensus data. However as the reference point, 1 cm falls in a very high gradient region of the radial profile, a minor fluctuation shows drastically different results. In this figure, it can be observed that the dose profile of 0.3 cm^3 Semiflex chamber visually seems quite different from the reference profile but statistically, they were close to each other and have similar behavior. To rule out this kind of misleading interpretation of results another reference point was chosen at 4 cm.

Figure 4: Graphical illustration of experimentally acquired radial function for all the five detectors compared to AAPM TG-43 consensus data normalized at reference point 1 cm.



The graphical analysis of radial functions for all the detectors compared to AAPM TG-43 consensus data for the reference point 4 cm is illustrated in Fig. 5. The normalization of radial dose function at radial distance 4 cm provided a comparatively better picture of detector responses for the experimental dosimetry in high gradient area of HDR brachytherapy source.

Figure 5: Graphical illustration of experimentally acquired radial function for all the five detectors compared to AAPM TG-43 consensus data normalized at reference point 4 cm.



Further, it was observed that Micro diamond (PTW 60019) detector was found to provide comparative results within 3.2% to TG-43 reference data for the radial range from 1 cm to 10 cm. The 0.125 cm^3 Semiflex ionization chamber (PTW 31010) was found to provide the best comparative results within 2.9% to TG-43 reference consensus data for the radial range from 2 cm to 14 cm and its best suited for the choice of the detector for experimental dosimetry for HDR brachytherapy. The behavior of 0.3 cm^3 Semiflex ionization chamber PTW 31013 was ambiguous for the radial range of few initial centimeters and after that observed to be well within 1.9% to TG-43 reference data for the radial range from 4 cm to 14 cm. Similar kind of observations was reported by Schoenfeld *et al* [5] and Rossi G *et al* [6]. Schoenfeld *et al* reported the suitability of micro-diamond detectors and small volume pinpoint chambers for experimental dosimetry for Ir-192 HDR brachytherapy sources [5]. Rossi G *et al* also advocated the uses of micro-diamond detector as a detector of choice for experimental dosimetry in HDR brachytherapy for clinically relevant radial distances up to 5 cm for Ir-192 source. However, they also have shown the suitability of pinpoint ionization chamber for experimental dosimetry on contrary to our observation in this work [6]. This contrary observation could be due to the difference in pinpoint chamber models used for both the study.

In case of Pinpoint ionization chamber PTW 31006, the detector over responded at larger radial distances, which can be attributed to its steel electrode. Similar behavior was also reported by Butler *et al* [13]. Unshielded Diode E PTW 60012 detectors was also found to over-respond with increasing radial distances. This behavior can be seen as the result of its high-energy dependence to low energy scattered radiations. Griessbach *et al* reported similar trends in the literature [14]. These two detectors Pinpoint ionization chamber and unshielded Diode E detector needs to be used with energy correction factors for experimental dosimetry in HDR brachytherapy due there high energy dependence.

This work has demonstrated that the detectors with small volume and low energy dependence are detector of choice for experimental dosimetry in HDR brachytherapy. It was observed that individual characteristics of the detector were more important instead of the basic type of the detector. Both the categories of detectors solid-state and ionization chambers have several suitable detector options for HDR brachytherapy dosimetry, especially for Co-60 source.

4. CONCLUSION

The present study has provided a reference design to perform experimental dosimetry in HDR brachytherapy for Co-60 source and also verifies the AAPM TG-43 consensus data experimentally. Suitability of various dosimeters were tested for experimental dosimetry and found that the detectors with small volume and low energy dependence are detector of choice for experimental dosimetry in HDR brachytherapy. Micro diamond and small volume Semiflex ionization chambers were found suitable for experimental dosimetry for the clinically relevant radial distance.

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