

## Determination of Tissue Phantom Ratios of High Energy Photon Beams Using Monte Carlo Code

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### ABSTRACT

Monte Carlo codes are veritable tools in radiotherapy to understand the transport mechanism, dose distributions, and energy depositions of ionizing radiations traversing in different media. In some beam calibration protocols, a tissue-phantom-ratio at depths 20 cm and 10 cm (TPR<sub>20,10</sub>) in a phantom is used to determine the beam-quality conversion factor for different ion chambers. Thus, this study aims to evaluate the efficiency of Monte Carlo code in the determination of beam quality of high radiation energy beams similar to what is expected in clinical settings. Electron Gamma Shower National Research Council in Canada (EGSnrc) Monte Carlo Code was used to design complex ion chamber geometries according to the manufacturer's specifications. Phase space files were used as x-ray beam radiation sources. Two set-ups (SAD and SSD) methods were used for the determination of TPR<sub>20,10</sub> to conform to the accepted clinical procedures. Beam collimation was 10 cm by 10 cm field size with an ionization chamber placed at 20 cm and 10 cm in the water phantom to obtain doses at two points respectively. The TPR<sub>20,10</sub> of each energy was obtained using the appropriate equations. The obtained results showed no significant difference between the measured and available TPR<sub>20,10</sub> data ( $p = 0.995$ ). Ion chamber configurations and specifications were also found not to have a significant effect ( $p = 0.33$ ) on the TPR<sub>20,10</sub> obtained values. The results obtained in this study are in agreement with the recommended standard values. The findings of this study show that the Monte Carlo codes can be used as a tool in determining x-ray beam quality indices of designed clinical linear accelerator (Linac) machines.

**Keywords:** Tissue phantom ratio, Monte Carlo, Beam quality, EGSnrc, Quality index, Simulation

### Introduction

Linear accelerator (LINAC) has been a vital piece of equipment in the radiotherapy department for treating cancer and other malignancies worldwide. Accurate dose delivery to the target with external photon or electron beams depends among other factors on the output of the radiation beam. To comply with the accurate measurements of

LINAC machine output using some dosimetric protocols; beam quality specification forms part of the parameters necessary to evaluate the correctness of the machine's nominal beam energy (IAEA, 2000; Khan, 2003; NCS, 2012). The beam quality index is mostly used by LINAC vendors to verify stated beam energy specifications and determine the appropriate

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beam-quality-correction factor for the ionization chamber (Sharma, 2008).

The specification of the quality of a photon beam has been studied and reported in the literature to amplify its relevance in radiation dosimetry (Sharma, 2008; Attalla *et al.*, 2008; Sauser and Wibert, 2009; Pelawi *et al.*, 2018). However, no beam quality specifier has been found to satisfy all possible requirements of being a unique specifier for the entire energy range of photon energies used in hospitals and standards laboratories (IAEA, 2000; Sharma, 2008). Nominal acceleration potential (NAP), percentage depth dose at 10 cm depth (D10), the depth of the 80% depth dose, and tissue-phantom ratio ( $TPR_{20,10}$ ) had been proposed as beam specifiers. Tissue-phantom ratio method has been reported to be within the range of the estimated uncertainty of stopping power and not affected by electron contaminations compared to other beam specifiers (IAEA, 2000; NCS, 2012).

In this study, the tissue-phantom ratio,  $TPR_{20,10}$  has been adopted since most dosimetry protocols recommended it to be most appropriate for the high energy quality beam quality specifications (Kosunen and Rogers, 1993). Numerically,  $TPR_{20,10}$  is the ratio of the absorbed doses at depths of 20 cm and 10 cm in a water phantom.  $TPR_{20,10}$  is obtained as a ratio of doses, therefore, it does not require the use of displacement correction factors at the two depths when cylindrical chambers are used. Also,  $TPR_{20,10}$  is unaffected by systematic errors at each depth, as the settings in the two positions will be affected equally (IAEA, 2000; NCS, 20012). Two methods can be used to determine  $TPR_{20,10}$  according to the TRS398 protocol (IAEA, 2000): Source-Surface-Distance (SSD) and Source-Axis-Distance (SAD) (also known as source-chamber-distance (SCD)). The SSD method involves setting the surface of the water phantom to 100 cm from the source and using a beam of 10 cm by 10 cm field size at the measurement depths of 20

g cm<sup>-2</sup> and 10 g cm<sup>-2</sup> in the water phantom. The SAD method involves setting the ion chamber at 100 cm from the source and using a 10 cm x 10 cm field size at the measurement depths of 20 g cm<sup>-2</sup> and 10 g cm<sup>-2</sup> in a water phantom.

The Monte Carlo method in radiotherapy dosimetry has become the most efficient and consistent tool for simulations in most fields related to radiotherapy. Its applications range from basic dosimetric quantities, like stopping-power ratios and perturbation correction factors for reference ionization chamber dosimetry, to fully realistic simulations of clinical accelerators, detectors, and patient treatment planning (Rogers *et al.*, 1995). In MC simulation, even in a heterogeneous media, all the aspects of electron and photon transport are taken into account (Kawrakow *et al.*, 2017; Andreo, 2018). Monte Carlo (MC) code is also a veritable tool to simulate and accurately report the dosimetric behavior of photons and charged particles traversing through a medium. It has been used extensively in the design of the LINAC head, evaluation of dose distributions during radiotherapy, shielding efficiency, etc. (Andreo, 2018; Kawrakow *et al.*, 2019; Ibitoye *et al.*, 2022). Some of the available MC code systems for simulating electron and photon transport in a medium are EGSnrc, GEANT4 (TOPAS), Penelope, Fluka, ETRAN, PHITS, and MCNP (Kawrakow *et al.*, 2000; Bielajew, 2007). The EGSnrc MC Software toolkit employed in this study has various tools to simulate the transport and interactions of photons, electrons, and positrons in the matter. It is distributed with a wide range of applications and aids in modeling complex geometries associated with the radiotherapy components and assessing energy and dose depositions into different media as described in Kawrakow *et al.*, 2002.

There is little data available on the applications of the Monte Carlo code to beam quality estimation, especially  $TPR_{20,10}$  (Andreo, 2018; Rasel *et al.*,

2020). Therefore, the EGSnrc Monte Carlo code technique is employed in this study to estimate the beam quality of high-energy beams in a water phantom by comparing the obtained results with the expected clinically available data.

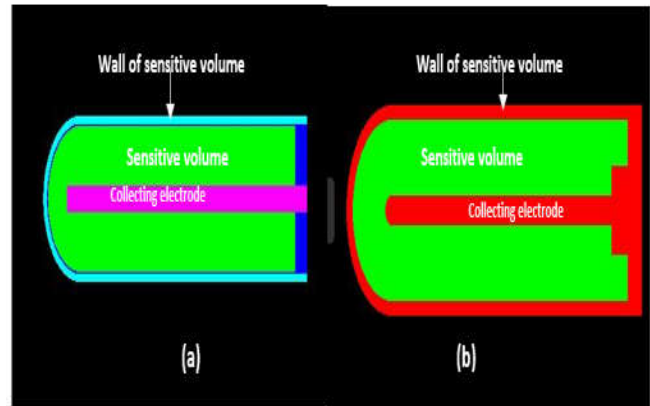
## Materials and Methods

EGSnrc Monte Carlo software was used in this study because it has excellent features to simulate and model complex geometries associated with the ionization chamber, LINAC head, and phantom. Its capability to allow set-up similar to what is obtainable in the clinical setting makes it a choice tool for this study.

### Simulation and Modelling

EGS++ application code in the EGSnrc Monte Carlo was used to model all geometrical components such as water phantom, radiation source, surrounding air, and ionization chambers. The geometry of the water phantom has a dimension of 60 cm × 60 cm × 60 cm to provide full scatter conditions. The simulated set-up was similar to the actual setting in the radiotherapy treatment room during calibration procedures. Modeling of Ionization Chambers Waterproof Exradin A12 (<https://static.standardimaging.com/literature/>) and PTW 30013 (<https://www.ptwdosimetry.com/en/detector-selector/>) ionization chambers were modeled according to specifications in their respective product manuals (Table 1) (Exradin Detectors, 2018; PTW Detectors, 2022).

Figure 1 is the designed geometric components of ionization chambers used in this study. The dimensions, materials, and density of the materials components as specified in the manufacturers' manual are shown in Table 1. Ionization chamber sensitive volume, thickness, and density of the wall of sensitive volume are the major factors that determine dose values collected during this study.



**Figure 1:** Simulated (a) PTW 30010 ionization chamber (b) Exradin A12 ionization chamber

Photon source: Different photon sources with varying beam energies were used. IAEA phase-space files for 6, 10, 15, and 25 MV were used as sources of radiation because they have been validated as reliable and also help to avoid the repetition of lengthy Monte Carlo calculations.

Input definitions: The input definitions such as the geometry, media, particle source, dose scoring, and run control definitions were combined and executed. Dose deposition in the sensitive volume of the ion chambers was scored using the available libraries in the code. All other transport parameters and options were left at their default settings.

### Measurement of $TPR_{20,10}$

As shown in Figure 2, SAD and SSD methods were used for the determination of  $TPR_{20,10}$  as discussed in the TRS398 protocol (IAEA, 2000). In the SSD method, the ratio of doses on the beam central axis at depths of 20 cm (D<sub>20</sub>) and 10 cm (D<sub>10</sub>) in water were determined by keeping the source-chamber-distance (SCD) constant at 100 cm and a field size of 10 × 10 cm<sup>2</sup> and apply equation (1)

$$TPR_{20,10} = \frac{D_{20}}{D_{10}} \quad 1$$

The SAD method was used to determine the ratio of the depth doses (DD<sub>20,10</sub>) at 20 cm and 10 cm depth, respectively using Equation 2

$$TPR_{20,10} = 1.2661 * \left(\frac{D_{20}}{D_{10}}\right) - 0.0595 \quad 2$$

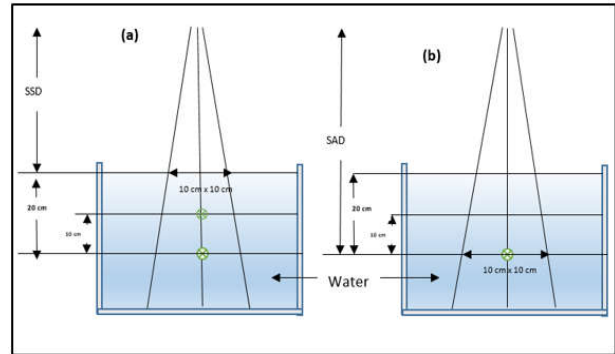
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The quotient of the D<sub>20</sub> and D<sub>10</sub> were substituted in equation 2 to obtain TPR<sub>20,10</sub>.

The points of measurement were on the beam's central axis. The chambers' axes were adjusted to 13.0 mm and 12.9 mm from the chamber tips of PTW 30013 and Exradin A12 ion chambers respectively as indicated in the detectors' brochures. Statistical analyses for all the data were performed using Statistical Package for Social Sciences (SPSS) version 23 (Armonk, NY, USA). Significance was based on p-value < 0.05.

Figures 3a and 3b show simulation setups of the SSD method and SAD method respectively. In

the SSD method the positions of the chamber change in the water phantom with the constant SSD. In the SAD method, the distance between the source and the chamber remains constant while the thickness of the water varies.



**Figure. 2:** TPR<sub>20,10</sub> simulation setup similar to the recommended clinical (a) SSD and (b) SAD methods (IAEA, 2000).

**Table 1:** Ionization chamber types and geometrical specifications

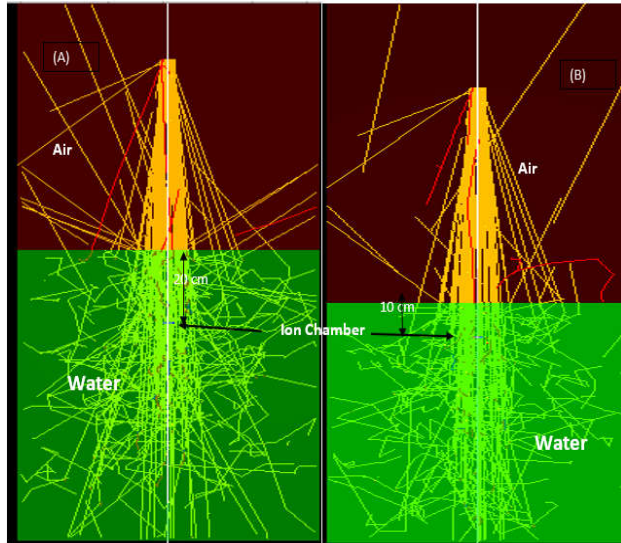
Chamber	Sensitive volume (air) (cm <sup>3</sup> )	Wall of the sensitive volume (thickness, density)	The radius of sensitive volume (mm)	Length of sensitive volume (mm)	Central Electrode (thickness)
PTW 30013	0.60	PMMA (0.335 mm, 1.19 g/cm <sup>3</sup> ), Graphite (0.09 mm, 1.85 g/cm <sup>3</sup> )	3.05	23.0	Al (1.15 mm)
Exradin A12	0.64	C-552 air-equivalent plastic (0.5 mm, 1.76 g/cm <sup>3</sup> )	3.05	21.6	C-552 (0.50 mm)

**Results**

Figures 3A and 3B show the geometrical setup to determine D<sub>20</sub> and D<sub>10</sub> using SAD 100 cm and a collimation field size of 10 cm x 10 cm. The figure includes the water phantom, air, and the ionization chamber position in the water phantom. Particle fluence distributions that include photons (brown), electrons (red), and positrons (blue) in the water and air are shown.

The radiation fluence distribution is dependent on the beam energy, field size, and the number of histories used.

Table 1 below shows measured doses at depths 20 cm and 10 cm, calculated, reference, and percentage difference of TPR<sub>20,10</sub> of different photon energy beams. The percentage difference between the calculated and reference values is within ±5% and no statistically significant difference was observed (p = 0.92)



**Figure 3:** A Cross-section of the SAD simulation method using a 25 MV phase space beam.

**Table 1:** TPR<sub>20,10</sub> distributions of different beam energies using PTW 30013 ionization chamber in a water phantom using the SSD method

Energy (MV)	D20 (10-15 Gy)	D10 (10-15 Gy)	TPR <sub>20,10</sub>		% diff
			Present study (D <sub>20</sub> /D <sub>10</sub> )	NPL Report <sup>†</sup>	
6.0	0.151	0.230	0.657	0.682	-3.503
10.0	0.493	0.669	0.737	0.733	0.595
15.0	0.863	1.144	0.754	0.755	-0.141
25.0	2.039	2.495	0.817	0.800	2.117

<sup>†</sup>Pearce and Bass, 2010

Table 2 below shows measured doses at depths 20 cm and 10 cm, calculated, reference, and percentage difference of TPR<sub>20,10</sub> of different photon energy beams. The percentage difference between the calculated and reference values is within ±5% and a statistically significant difference was observed (p = 0.08).

**Table 2:** TPR<sub>20,10</sub> distributions of different beam energies using Exradin A12 ionization chamber in a water phantom using the SSD method

Energy (MV)	D20 (10-15 Gy)	D10 (10-15 Gy)	TPR <sub>20,10</sub>		% diff
			Present study (D <sub>20</sub> /D <sub>10</sub> )	NPL Report <sup>†</sup>	
6.0	0.158	0.234	0.675	0.682	-1.059
10.0	0.533	0.764	0.698	0.733	-4.779
15.0	0.950	1.282	0.741	0.755	-1.879
25.0	1.951	2.557	0.763	0.800	-4.604

<sup>†</sup>Pearce and Bass, 2010

Table 3 shows measured doses at depths 20 cm and 10 cm, calculated reference, and percentage difference of TPR<sub>20,10</sub> of different photon energy beams. The percentage difference between the calculated and reference values is within ±5% and no statistically significant difference was observed (p = 0.33)

**Table 3:** TPR<sub>20,10</sub> distributions of different beam energies using PTW30013 ionization chamber and SAD method in a water phantom

Energy (MV)	D20 (10-15 Gy)	D10 (10-15 Gy)	D <sub>20</sub> /D <sub>10</sub>	TPR <sub>20,10</sub>		% diff
				Present study (D <sub>20</sub> /D <sub>10</sub> )	NPL Report <sup>†</sup>	
6.0	0.130	0.221	0.586	0.685	0.682	0.079
10.0	0.372	0.593	0.628	0.735	0.733	0.272
15.0	0.622	0.933	0.667	0.785	0.755	3.928
25.0	0.651	0.958	0.680	0.801	0.800	0.115

<sup>†</sup>Pearce and Bass, 2010

Table 4 shows measured doses at depths 20 cm and 10 cm, calculated reference, and percentage difference of TPR<sub>20,10</sub> of different photon energy beams. The Percentage difference between the calculated and reference values is within ±5%

and no statistically significant difference was observed ( $p = 0.13$ )

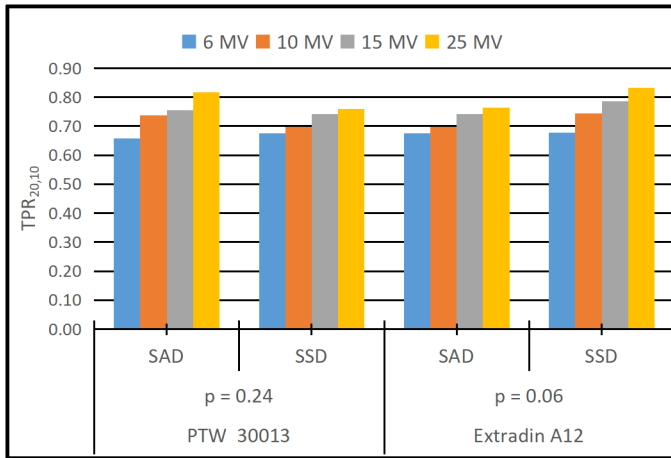
**Table 4:** TPR<sub>20,10</sub> distributions of different beam energies using Exradin A12 ionization chamber and SAD method in a water phantom

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Energy (MV)	D20 (10-15 Gy)	D10 (10-15 Gy)	$\frac{D_{20}}{D_{10}}$	TPR <sub>20,10</sub>		% diff
				Present study ( $D_{20}/D_{10}$ )	NPL Report †	
6.0	0.105	0.180	0.583	0.678	0.682	-0.578
10.0	0.388	0.611	0.635	0.744	0.733	1.513
15.0	0.679	1.018	0.667	0.785	0.755	3.911
25.0	1.468	2.085	0.704	0.832	0.800	4.003

†Pearce and Bass, 2010

Figure 4 shows the TPR<sub>20,10</sub> using different ionization chambers. The figure shows no significant difference between SAD and SSD methods using PTW30013 ( $p = 0.24$ ) and Exradin A12 ( $p = 0.06$ ).



**Figure 4:** Comparison between TPR<sub>20,10</sub> distributions with different ionization chambers

**Discussions**

A phase space contains data relating to particle position, direction, charge, etc. for every charged particle crossing a plane. These data are most commonly used to transfer a set of particles in the Monte Carlo codes in the study of the transportation of radiation beams through media. This always helps to reduce the complexity of designing associated with the manufacturers’ specifications.

It is essential to know the radiation beam quality specification in the dosimetric protocols to accurately obtain the absorbed dose to water at a reference point in the water phantom. Beam quality is used to describe the penetrability of radiation beam energy.

Most TPR<sub>20,10</sub> values reported in the literature have been based either on analytical procedures or experimental methods with little data on its verification using the Monte Carlo code method (Kosunen and Rogers, 1993). The obtained results in this study are in agreement with TPR<sub>20,10</sub> obtained in the National Physical Laboratory (NPL) on the Elekta LINAC machines (Pearce and Bass, 2010). There is no significant difference between TPR<sub>20,10</sub> obtained in this study and those reported in the literature and radiotherapy department (Boutillon *et al.*, 1994; Narayanasamy *et al.*, 2015). In addition, the average values of TPR<sub>20,10</sub> obtained using different ion chambers and different methods are not statistically significant ( $p = 0.801$ ). The percentage differences between these two ion chambers are within  $\pm 5\%$ . Apart from being used to indicate a particular value of nominal x-ray energy, most dosimetry protocols, based on both standards of air kerma and standards of absorbed dose to water, have recommended the Tissue-Phantom Ratio, TPR<sub>20,10</sub>, as specifiers of the quality of a high-energy photon beam (Kinoshita *et al.*, 2017). Based on the data obtained in this study, the EGSnrc Monte Carlo code can be used to calculate dosimetric parameters especially

tissue-phantom-ratio apart from being a veritable tool to design complex geometries of the radiotherapy machines.

### Conclusion

Relative doses at 20 cm and 10 cm in a water phantom (TPR<sub>20,10</sub>) of different photon energy beams have been estimated in this study. EGSnrc Monte Carlo code was used to design the water phantom, ionization chambers, and placement of the ion chambers in the appropriate position in the water phantom to mimic real-time setup. No significant differences were observed between the calculated TPR<sub>20,10</sub> and the data available in the literature and the clinics. Small variations in the dose collected at the point of measurement were observed to depend on the type of ion chamber used and the choice of setup (SSD or SAD method) but with no significant difference. Conclusively, this study establishes that the EGSnrc Monte Carlo code is an efficient tool to determine tissue phantom ratio and other dosimetric parameters associated with radiotherapy linear accelerator machine.

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**Competing Interest:** None.

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