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| RESEARCH ARTICLE

Determination of Beam Quality and Dosimetric Verification of 6MV and 10MV Photon Beam of an Elekta Synergy Platform Linear Accelerator

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| ABSTRACT

Beam quality verification is a fundamental aspect of radiotherapy commissioning and quality assurance, ensuring that photon beams from medical linear accelerators correspond to their nominal energies and comply with international dosimetry protocols. For megavoltage beams, indices such as percentage depth dose (PDD) at 10cm, tissue phantom ratio at depths of 10cm and 20cm ($TPR_{20,10}$), and quality conversion factor $kQ_, Q_0$, are used to characterize beam quality. Accurate measurement of these parameters is essential to achieving consistent dose delivery and maintaining patient safety. This study aims to determine and verify the beam quality of 6MV and 10MV photon beams from Elekta Synergy linear accelerator for treatment plan quality assurance. Beam quality measurements were performed in water in a 3D water phantom at 100cm source-to-chamber distance (SCD) of 100cm and a field size of 10cm x 10cm at the chamber plane. A calibrated cylindrical Farmer type ionization chamber (30010) connected to a calibrated PTW UNIDOS electrometer (60731) was used to obtain depth-dose readings, the $kQ_, Q_0$ value were then evaluated using the IAEA TRS 398 $TPR_{20,10}$ method. Measurements were taken at depths of 20cm and 10cm beneath the water surface, and at three different polarities of +300, +150, and -300 polarities on the electrometer. For the 6MV photon beam, the $kQ_, Q_0$ value was 0.993, $TPR_{20,10}$ was 0.67, PDD(10) was 66.38% and the absorbed dose to water at Zmax was 0.9941cGy/MU and for the 10MV photon energy, the $kQ_, Q_0$ value was 0.983, $TPR_{20,10}$ was 0.73, the PDD was 74.8% and the absorbed dose to water at Zmax was 1.004cGy/MU, these values are consistent with international reference standards. Beam quality verification confirmed that the Elekta Synergy linear accelerator delivers accurate 6MV and 10MV photon beams in compliance with TG-51 and IAEA TRS-398. Routine quality checks remain essential to ensure precise dose delivery and optimize radiotherapy outcomes.

| KEYWORDS

Absorbed dose to water, Beam quality index (BQI), Mega voltage photon beam, Tissue phantom ratio (TPR), Percentage depth dose (PDD).

| ARTICLE INFORMATION

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1. Introduction

Contemporary methods in radiation therapy necessitate the administration of substantial radiation doses with heightened precision. Research has shown that the efficacy of radiation treatment is contingent upon the absorbed dose received by the tumor, which should not deviate by more than a few percent from the prescribed levels.

Consequently, the International Commission on Radiation Units and Measurements (ICRU) has determined that an accuracy of ±5% in the delivery of absorbed dose is essential in certain treatment scenarios [Brevitt, 2018]. The field of radiation therapy has undergone significant advancements, with various methods of radiation techniques now in use. These methods include the controlled emission of gamma rays from a Cobalt-60 source, as well as the generation of particles such as photons, electrons, and protons through linear accelerators. The specific characteristics and location of the tumor volume determine the strategy for administering the radiation dose, ensuring comprehensive coverage of the tumor. This evolution has progressed from three-dimensional conformal therapy (3-D CRT) to more sophisticated techniques such as Intensity Modulated Radiation Therapy (IMRT), Intensity Modulated Proton Therapy (IMPT), Image Guided Radiation Therapy (IGRT), and Volumetric Modulated Arc Therapy (VMAT).To implement these diverse specialized techniques, a growing number of treatment centers are adopting multimodality treatment units. However, the technical intricacies associated with these units introduce potential risks that are typically absent in single modality units. Such issues may include software defects, equipment malfunctions, programming errors, insufficient expertise, and inadequate safety protocols, all of which can result in radiation overexposure to patients during treatment. In the context of radiotherapy, an accident refers to any significant unintended occurrence, such as an operational mistake, equipment malfunction, or other unforeseen incident, whose implications cannot be overlooked in terms of safety or protection [Coeytaux, 2015]. Such events typically result in the risk of excessive exposure or abnormal exposure scenarios for the patient receiving treatment, the medical staff, or the general public. Medical exposures are usually intended to provide a direct benefit to the exposed individual. If the practice is justified and the protection and safety optimized, the dose in the patient will be as low as is compatible with the medical purpose, any further application of limits might be to the patient's detriment. Recent incidents involving radiation accidents that led to excessive exposure of radiotherapy patients have highlighted the significant repercussions of equipment malfunctions in linear accelerator treatment units. Accounts of these events have been documented in publications by the American Medical Association (AMA) and International Atomic Energy Agency (IAEA). A National Library of Medicine (NLM) publication of 2015 titled "Reported Radiation Overexposure Accidents by Sector and Type of Exposure Worldwide, 1980 – 2013" indicated that among the 634 accidents documented during the study period, radiation therapy accounted for the highest number of radiation overexposure incidents, totaling 202 cases, this was followed by Fluoroscopy with 194 cases, Industrial incidents with 169 cases, other categories with 33 cases, Orphan Sources with 32 cases, and Military incidents with 1 case [ICRU,1976]. Medical linear accelerators experience more frequent downtimes and exhibit higher component failure rates in low and medium income countries (LMICs), due extended usage, leading to fluctuation in treatment beam energy, compared to those in high-income nations. In Nigeria, there is a deficit of around 280 linacs, which results in regular downtimes attributed to extended usage [Obinna,2020]. Photons with energies exceeding 1.022 MeV, or roughly 1 MV, can interact with the medium resulting in beam contamination. This study focuses on nominal energies of 6 MV and 10 MV, which are significantly above the threshold for such interactions to occur. Consequently, during treatment, interactions with the gantry components may occur, generating particles that could contaminate the photon treatment beam, which may lead to fluctuations in photon energy, potentially resulting in radiation overexposure to the patient during the treatment process. In this study, the quality assurance (QA) process is being implemented to assess beam quality and perform dosimetric verification of the treatment beam. This procedure aims to evaluate the consistency of beam energy and output, as well as the precision of dosimetry measurements. It is essential to ensure that the treatment beams remain within the baseline values established during the commissioning, testing, and acceptance phases of the linear accelerator.

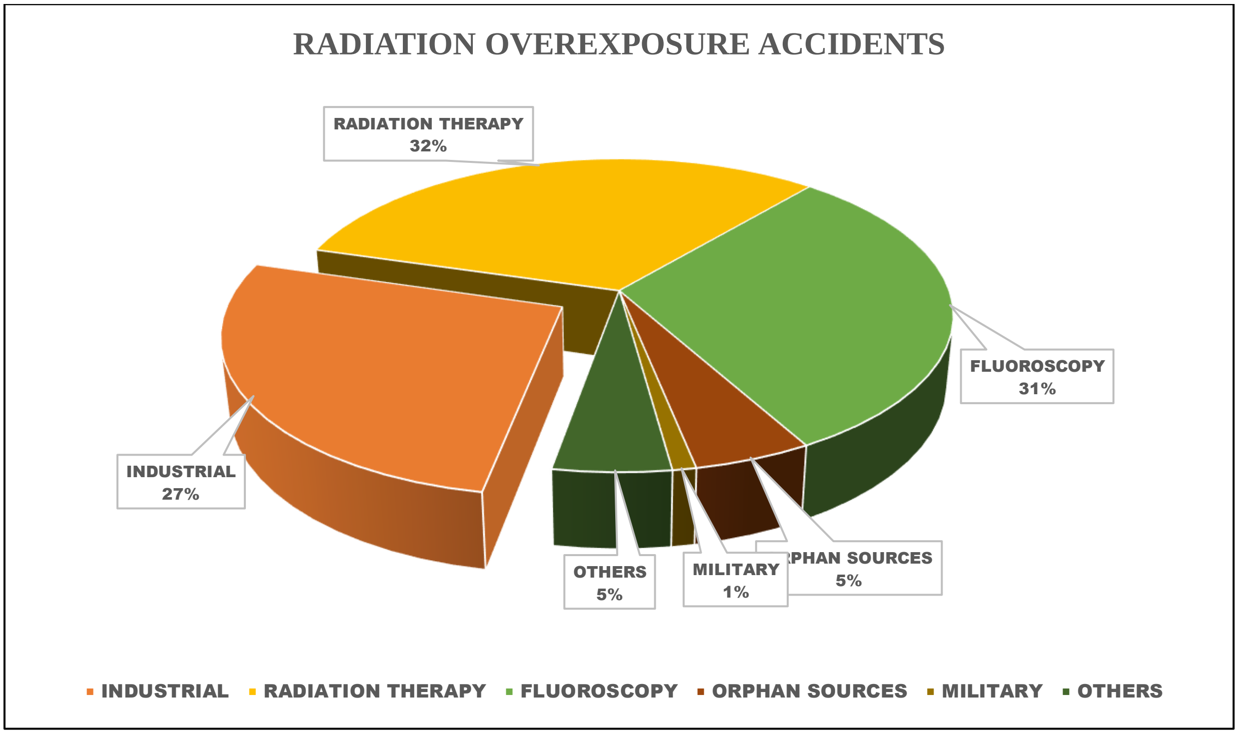

Fig 1: Reported Cases of Radiation Overexposure Accidents

2. Materials and Methods

The determination of the beam quality index Q and the Absorbed dose in water $D_{W,\,Q}$ were performed under the conditions defined by the IAEA TRS 398 code of practice protocol. A Farmer type ionization chamber (30010) along with a PTW UNIDOS electrometer was utilized to measure ionization charges for both the 10MV and 6MV beam produced by an Elekta Synergy linear accelerator. The measurements were conducted using a 3D water phantom, maintaining a source to detector distance (SCD) of 100 cm, with the chamber positioned 10 cm below the water surface with a field size of 10cm x 10 cm at the plane of the ionization chamber. The TRS 398 protocol was used to calculate the beam quality index *Q*. The quality correction factor $kQ,\ Q_{o,}$ corrects for the difference between the response of an ionization chamber in the reference beam quality Q_0 and in the actual user beam of quality *Q*, when the reference quality is ^{60}Co gamma radiation. The beam quality index *Q* is normally used for absolute dosimetry of high energy photon radiation with ionization chambers, to correct the spectral difference between the spectrum of the calibration radiation ^{60}Co and the spectrum of therapeutic radiation. Measurements were taken twice, one at depths of 20 cm and the other at 10 cm below the water surface, with a source-to-chamber distance of 100 cm. For both photon energies, three measurements were recorded at polarities of +300, -300, and +150.

Figure 2: Linear Accelerator Treatment Head

2.1 *Beam Quality and Absorbed Dose Measurements.*

Absorbed dose is a dose quantity that is the measure of the energy deposited in matter by ionizing radiation per unit mass. Its formal definition is the quotient.

$$D = \frac{dE}{dm} \qquad 1$$

Where dE is the mean energy imparted by ionizing radiation to matter of mass dm. The unit by which Absorbed dose is specified is $J.kg^{-1,}$ and the special name for this is gray. $1Gy = 1J.kg^{-1}$

The IPSM Code of Practice for high-energy photon beams (IPSM 1990) identifies the tissue-phantom ratio, $TPR_{20,10}$, as a key indicator of the quality of high-energy photon beams. This specification is widely endorsed in various radiation dosimetry protocols, including the IAEA technical report TRS 398 (2000), IAEA technical report 277 (1987), and NCS (1986).

$$TPR_{20,10} = \frac{D_{20}}{D_{10}} \qquad 2$$

Tissue phantom ratio *(TPR)* is defined as the quotient between the absorbed dose (or absorbed dose rate) in a phantom and the dose at the same point at a fixed reference depth. When the reference depth corresponds to the maximum absorbed dose depth, the ratio is named the Tissue Maximum Ratio *(TMR)*

$$TMR(z, f_{clin}) = \frac{D(z,f_{clin})}{D(z_{max},f_{clin})} \qquad 3$$

Where Z and Z_{max} represent the depth and the depth at maximum dose.

Percentage Depth Dose distribution *(PDD)* represents the relative absorbed dose deposited by a radiation beam into a medium as it varies with depth along the axis of the beam. The dose values are normalized at the maximum dose, yielding a plot in terms of percentage of the maximum dose.

$$\boldsymbol{PDD(z, f_{clin})} = \frac{D(z, f_{clin}, F)}{D(z_{max}, f_{clin}, F)} \qquad 4$$

Where Z and Z_{max} represent the depth and the depth at maximum dose, f_{clin} is the clinical field size, r is the distance from the central axis, and F is the source-to-surface distance.

2.2 *The $N_{D,w}$ based Formalism*

When a dosimeter is used in a beam of quality Q, different from that used in its calibration, Q_o, the absorbed dose to water is given by

$$D_{w,Q} = M_Q \; N_{D,w,Qo} \; k_{Q,Q0} \qquad 5$$

$k_{Q,Q0}$ can be obtained as,

$$k_{Q,Qo} = \frac{N_{D,w,Q}}{N_{D,w,Qo}} = \frac{D_{w,Q}/M_Q}{D_{w,Qo}/M_{Qo}} \qquad 6$$

$$M_Q = M_{raw} \; X \; k_{TP} \; X \; k_{elec} \; X \; k_{pol} \; X \; ks \qquad 7$$

Where, $D_{w,Q}$ is the absorbed dose to water, $N_{D,w,Qo,}$ is the calibration factor for the reference energy, $k_{Q,Q0}$ is the correction factor which corrects $N_{D,w,Q0}$ for the difference between the reference beam quality Q_0 and the actual beam quality Q, M_Q and M_{raw} are the corrected and the raw meter readings, K_{TP} is the temperature, pressure correction factor, K_s is the ion recombination correction factor, K_{elec} a factor allowing for separate calibration of the electrometer, K_{pol} is the polarity correction factor.

$$k_{TP} = \frac{P_0}{P} \times \frac{T + 237.2}{T_0 + 237.2} \qquad 8$$

,

$$k_{pol} = \frac{|M_+| + |M_-|}{2M} \qquad 9$$

$$k_s = a_0 + a_1 \frac{M_1}{M_2} + a_2 \left(\frac{M_1}{M_2}\right)^2 \qquad 10$$

Where: P_o is the pressure at calibration, T_0 is the temperature at calibration, P is the measured pressure, and T is the measured temperature. While P_o = 101.3 KPa and T_o = 20°C are pressure and temperature values at reference conditions, $M+$, $M-$, *and* M are the positive, negative, and the routine polarity readings; a_0, a_1 and a_2 are the quadratic fits coefficients.

3. Results and Discussion

Equations 2, 5, 7, 8, 9, and 10 were used to evaluate the various parameters using the IAEA TRS 398 code of practice protocol.

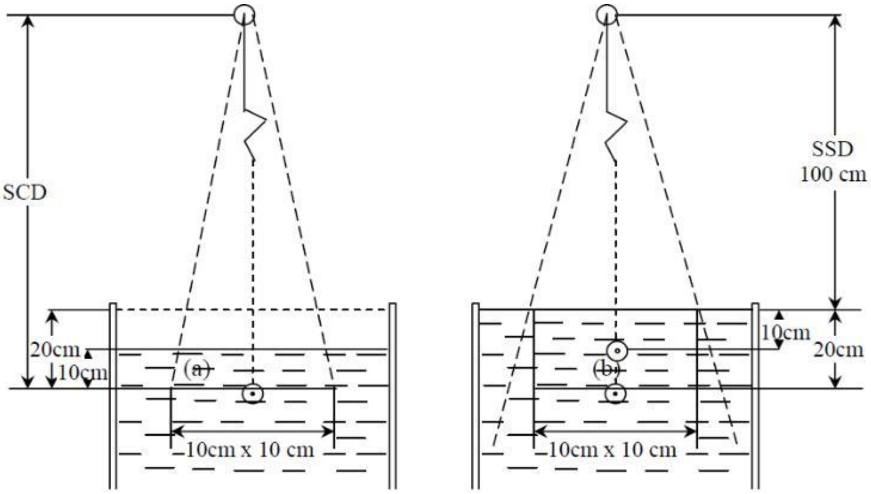

Figure 3: Method for Beam Quality Determination

Table 1: The $TPR_{20,10}$ and $K_{Q,Q0}$ for 6MV and 10MV Photon Energy

Photon Beam	$TPR_{20,10}$	$K_{Q,Q0}$
6MV	0.67	0.993
10MV	0.73	0.983

Using equation 2, the tissue phantom ratios were evaluated to be 0.67 and 0.73 for 6MV and 10MV, respectively. The values were then used to get $K_{Q,Q0}$ values for the two photon energies, the values were 0.993 and 0.983 for 6MV and 10MV, respectively.

Table 2: Linear Accelerator Nominal Energy and Beam Quality Indicator

Nominal Energy (MV)	**Beam Quality Indicators**		
	D_{10} %	**dm(cm)**	$TPR_{20,10}$
6	67.5	6.70	0.676
8	71.00	7.50	0.703
10	73.00	8.00	0.724
12	75.00	8.50	0.740
15	77.00	9.10	0.755
18	79.00	9.70	0.771
21	81.00	10.30	0.777
25	83.00	10.9	0.781

Table 3: Linear Accelerator Beam Quality Index *(BQI)* Comparison

Nominal Beam	$TPR_{20,10}$ (NPL)	$TPR_{20,10}$ (Sharma)	$TPR_{20,10}$ (This Study)
6MV	0.682	0.676	0.67
10MV	0.730	0.724	0.73

Comparing this study with two other studies, the tissue phantom ratios for this study were 0.67 and 0.73, which are in good agreement with the two other studies above, that are 0.682, 0.730, and 0.676, 0.724 for 6MV and 10MV, respectively.

3.1 *Determination of Absorbed Dose to Water at the Reference Depth Z_{ref} in Water*

Table 4: Reference Conditions for the Determination of Absorbed Dose of high Energy Photon Beam

Influence Quantity	Reference Value
Phantom Material	Water
Chamber Type	Cylindrical
Measurement Depth, Z_{ref}	for $TPR_{20,10}$ 10g/cm2
Reference Point of the Chamber	central axis, centre of the cavity volume
Position of the Reference Point	at measurement depth Z_{ref}
SSD/SCD	100cm

Table 5: Values for the Calculation of M_Q for 6MV and 10MV Photon Energy

Influence Quantities	6MV	10MV
K_{tp}	1.065	1.077
k_{pol}	1.000	1.002
k_s	1.000	1.002
K_{elec}	1.000	1.000

K_{elec} = 1, since the electrometer and the chamber were jointly calibrated

$M_{Q,}$ values are 0.1293 nC MU^{-1} (6MV) and 0.1486 nC/MU^{-1} (10MV)

$K_{Q,Q0}$ values are 0.993 (6MV) and 0.983 (10MV)

Using equation (5), the absorbed dose to water at Z_{ref}, $D_{W,Q}(Z_{ref})$ for 6MV and 10MV are

0.6599cGy/MU and 0.751 cGy/MU respectively.

3.2 *Determination of Absorbed Dose to Water at (Z_{max}) for 6MV and 10MV*

Absorbed Dose to Water at Z_{max} for 6MV SSD Set-up:

Percentage depth dose (PDD) at Z_{ref} for 10cm x 10cm field size, PDD (Z_{ref} = 10g/cm^2) = 66.38%

$D_{W,Q}(z_{max}) = 100\ D_{W,Q}(z_{ref}) / PDD(z_{ref})$ = 0.6599/0.6638 = 0.9941 cGy/MU

Absorbed Dose to Water at Z_{max} (10MV) SSD Set-up:

Percentage depth dose (PDD) at Z_{ref} for 10 x 10cm field size, PDD (Z_{ref} = 10g/cm^2) = 74.80%

$D_{W,Q}(z_{max}) = 100\ D_{W,Q}(Z_{ref}) / PDD(Z_{ref})$ = 0.751/0.748 = 1.004 cGy/MU

Table 6: M_Q, *PDD,* and Absorbed Dose at Z_{ref} and Z_{max}

Photon Energy	M_Q	*PDD*	$D_{W,Q}(z_{ref})$	$D_{W,Q}(z_{max})$
6MV	0.1293	66.38%	0.6599	0.9941
10MV	0.1486	74.80%	0.7510	1.0040

Table 6, outlines the absorbed dose to water at Z_{max} for this study, which were 0.9941cGyMU^{-1} and 1.040 cGyMU^{-1} for 6MV and 10 MV, respectively.

Table 7: Comparing Absorbed Dose in Water with ICRU Value

Photon Energy	ICRU ±5% Tolerance	$D_{W,Q}(z_{max})$ This Study	Deviations
6MV	1MU ☐ 1cGy	0.9941cGy MU^{-1}	- 0.59%
10MV	1MU ☐ 1cGy	1.0040 cGy MU^{-1}	+ 0.40%

Table 7 illustrates the absorbed dose at Zmax for this study alongside ICRU value; values from the study are well within the ICRU tolerance level.

The American Association of Physicists in Medicine AAPM-40 recommendation stipulates that dose delivered to a patient must be kept as close as possible to the prescribed dose and numerically within ±5% of the prescribed dose, and the International Commission on Radiation Units and Measurements ICRU 50 and 62 recommend that dose delivered to the patient must be (-5%, +7%). A clinical linear accelerator must, in all circumstances, function within the very narrow tolerances obtained at the time of acceptance testing. In this study, the absorbed dose to water at D_{max} for 6MV and 10MV photon energies were calculated to be 0.9941 cGy/MU (0.9941cGy = 1MU) and 1.004 cGy/MU (1.004cGy = 1MU), which have deviations of - 0.592% and 0.399% of (1MU = 1cGy), which are in tandem with ICRU 50 and 62 as well as TRS 398 protocols. In a similar study, the absorbed dose of the treatment unit at Dmax was calculated to be (18MV) 1.03 cGy/MU and (6MV) 1.03 cGy/MU, which have a deviation of 2.9%, though the results vary significantly with this study's, but it is still within the 3% tolerance [Sharma, 2008].

4. Conclusion

The intricate nature of photon generation and their interactions, along with the necessity for accurate targeting of tumor volumes, makes the verification of beam quality of utmost importance. It is essential that beam verification is performed daily prior to the commencement of treatment. The results from this study indicate that all specified variables remained within the established tolerances. Consequently, it can be concluded that the level of beam contamination in the Elekta Synergy Platform is minimal. Should quality assurance assessments identify any beam contamination or discrepancies from the anticipated absolute dose, the unit must be withdrawn from clinical application. The objective of all radiation procedures is to maintain the radiation dose at a level that is As Low as Reasonably Achievable (ALARA).

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