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Evaluation of Air-Kerma and Absorbed Dose to Water for External Radiotherapy Beam Using Ionization Chamber

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Abstract

Radiotherapy is the most widely applied oncologic treatment modality utilizing ionizing radiation. A high degree of accuracy, reliability and reproducibility is required for a successful treatment outcome. Measurement using ionization chamber is a prerequisite for absorbed dose determination for external beam radiotherapy. Calibration coefficient is expressed in terms of air kerma and absorbed dose to water traceable to Secondary Standards Dosimetry Laboratory. The objective of this work was to evaluate the level of accuracy of ionization chamber used for clinical radiotherapy beam determination. Measurement and accuracy determination were carried out according to IAEA TRS 398 protocol. Clinical farmers type ionization chamber measurement and National Reference standard from Secondary Standards Dosimetry Laboratory were both exposed to cobalt-60 beam and measurement results compared under the same environmental conditions. The accuracy level between National Reference Standard and clinical radiotherapy standard was found to be −1.92% and −2.02% for air kerma and absorbed dose to water respectively. To minimize the effect of error and maximize therapeutic dose during treatment in order to achieve required clinical outcome, calibration factor was determined for air kerma (N_k) as 49.7 mGy/nC and absorbed dose to water N_D, as 52.9 mGy/nC. The study established that radiotherapy beam measurement chain is prone to errors. Hence there is a need to independently verify the accuracy of radiation dose to ensure precision of dose delivery. The errors must be accounted for during clinical planning by factoring in calibration factor to minimize the systematic errors during treatment, and thereby providing enough room to achieve ±5% dose delivery to tumor target as recommended by ICRU.

Keywords

Absorbed Dose to Water, Air Kerma, Co-60 Source, Calibration, SSDL, Radiotherapy Beam, Metrology, Accuracy and Accuracy

1. Introduction

Kenya has in recent years experienced tremendous increase of radiotherapy facilities in the country referral hospitals for treatment of cancer [1]. The use of ionizing radiation for treatment of cancer has evolved from use of cobalt-60 source to linear accelerator for clinical practice [2]. The development of new techniques has led to an increase in complexity of procedures, instrumentation, planning, diagnostic and treatment. A clear and consistent method of measurement, modelling, dose delivery and reporting is necessary for successful curative treatment [3]. The overall accuracy of dose delivered to the patient is generally recommended to be within ±5% of the prescription at the 95% confidence level. TLD audit carried out by IAEA indicates that 12% of radiotherapy centers have challenges meeting the accuracy of ±5% [4] and on that account there is a need to carry out air kerma and absorbed dose to water measurement.

Accuracy is an important pillar in determination of success of radiation therapy. Errors in dose delivery can result in normal tissue damage [5]. Absorbed dose to water calibration is consequently important to radiotherapy facility to ensure accurate determination of dose delivery to tumors [6]. Clinical dosimetry measurement based on absorbed dose to water calibration factor are considerably accurate and have reduced uncertainty in comparison to air kerma dose measurement [7]. Besides, absorbed dose to water relates closely to the biological effects of radiation as tissue equivalent [8]. Furthermore, it ensures a high degree of accuracy, reliability, and reproducibility as required for safe and effective radiation treatment [9].

Dosimetry measurement is an effective tool for identifying accuracy challenges and addressing its non-conformities [10]. Dosimetric chain largely affect the level of accuracy of ionization chamber, from calibration factor in terms of air kerma measured in air using a Cobalt-60 beam to absorbed dose to water measured in water in clinical beams [11]. Absorbed dose methodology results into reduced uncertainty and use of simple formalism.

To ensure harmonization and consistency in radiotherapy, dosimetry measurement must be linked to International System. The accuracy level of ionization chamber should be determined at a designated competent National Laboratory, traceable to International Standards [12]. In this regard, absolute dosimetry is significantly important in linking hospital treatment directly with the International System [8]. The National Laboratory environmental conditions are controlled, and therefore the reference condition ensures calibration coefficient is valid without further corrections of influence quantities [13].

A study carried out by in Kenya [1] found out there is increase of radiotherapy services using increasingly high dose and no investigation has been done to ascertain the level of accuracy during treatment. Calibration of ionization chamber is not mandatory in Kenya and that being the case, the level of radiotherapy accuracy is at the discretion of hospital management. Consequently, introduction of linear accelerator in these facilities has placed greater opportunity for assessment of dose delivery during treatment for successful treatment outcome [14]. Accuracy and traceability of radiotherapy beams are therefore key critical factors for realizing curative outcome [9].

2. Materials and Methods

Radiation quantities

Kerma is the kinetic energy released per unit mass and quantifies the average amount of energy transferred from indirectly ionizing radiation to directly ionizing radiation [2].

The relation between the exposure X and air kerma is given by:

$$\text{Air kerma, } K_{air} = X\left(\frac{W_{air}}{e}\right)\frac{1}{1-\bar{g}} \tag{1}$$

where:

X is the exposure.

$\frac{W_{air}}{e}$ is the collision kerma.

$\bar{g}$ is the radiative fraction, representing fraction of the energy transferred to electrons lost through radiative processes.

The absorbed dose to the tissue of the patient is the main quantity of interest in radiotherapy. Human tissue consists of mainly water and therefore the quantity absorbed dose to water, D_w is used as a reference [8]. In this regard, absorbed dose is defined as the mean energy $\acute{\varepsilon}$ imparted by ionizing radiation to matter of mass m in a finite volume V by:

$$D = \frac{\mathrm{d}\acute{\varepsilon}}{\mathrm{d}m} \tag{2}$$

where

$\acute{\varepsilon}$—the sum of all the energy entering the volume of interest minus all the energy leaving the volume, taking into account any mass-energy conversion within the volume.

m—matter of mass in a finite volume.

Charge Q and air mass m_{air} are related to absorbed dose in air D_{air} by:

$$D_{air} = \frac{Q}{m_{air}}\left(\frac{W_{air}}{e}\right) \tag{3}$$

where:

Q is charge measured by ionization chamber.

m_{air} is the chamber sensitive air mass.

$\frac{W_{air}}{e}$ is the mean energy required to produce an ion pair in air per unit charge.

The absorbed dose to water D_{w,Q_0} at the reference depth Z_{ref} in water for a reference beam of quality D_{w,Q_0} given by:

$$D_{w,Q_0} = M_{Q_0} N_{D,W,Q_0} k_{Q,Q_0} \tag{4}$$

where

M_{Q_0} corrected chamber reading under the reference conditions used in the laboratory.

N_{D,W,Q_0} is the calibration coefficient of the absorbed dose to water of the chamber.

Q beam of quality.

Q_0 beam quality that was used during calibration.

k_{Q,Q_0} correction for the radiation quality of the beam.

The cavity air calibration coefficient $N_{D,air}$ is defined as:

$$N_{D,air} = \frac{D_{air}}{M_Q} \tag{5}$$

where

M_Q is the chamber signal corrected for influence quantities.

D_{air} absorbed dose to air in the cavity.

The accuracy of the ionization chamber (UUT) under test is determined by

$$\text{Accuracy} = \frac{\text{UUT chamber} - \text{SSDL chamber}}{\text{SSDL chamber}} \times 100 \tag{6}$$

where

UUT chamber—ionization chamber under test.

SSDL chamber—Ionization chamber reading from the SSDL considered as the reference.

Figure 1. Reference ionization chamber used for calibration of clinical radiotherapy detectors.

Figure 1 shows Ionization chamber used in this investigation, which is a gas filled cavity type [2]. It's made of graphite cavity chamber with accurately known chamber volume, designed to fulfil the requirements of a Bragg-Gray detector. The chamber is inserted in a water phantom and the absorbed dose to water at the reference point derived from the mean specific energy imparted to the air of the cavity [8].

Electrometer connected to the ionization chamber is used in the investigation because of its capability of measuring small currents and charge [2]. It is designed with features of high gain, negative feedback and operational amplifier with a standard capacitor in the feedback path to allow measurement of chamber current or charge over a fixed time interval. The output of the beam is measured with chambers having calibration coefficients traceable to a standards laboratory and is therefore used as relative dosimeters [15]. The beam measurement of SSDL is controlled from the controlled panel as shown in Figure 2.

Figure 2. Cobalt-60 radiotherapy control panel for irradiating ionization chamber.

Water is the standard phantom and universal soft tissue material for dosimetry measurement of electron and photon beams [2]. For photon beams, tissue equivalency implies a match in mass-energy absorption coefficient, mass stopping power and mass scattering power of water, thereby meeting water equivalent [8].

Measurement

The ionization chambers used for absolute dose measurement must be traceable to Primary Standards Dosimetry Laboratory (PSDL). The PSDL use measurement method of primary character to determine the absorbed dose to water according to its definition and disseminate absorbed dose to water to the Secondary Standards Dosimetry Laboratory (SSDL). Measurement was carried out at KEBS SSDL as shown in Figure 3.

Two ionization chambers were used for investigation, with one considered as a reference and traceable to the Secondary Standards Dosimetry Laboratory, while the other chamber was used as a subject of investigation considering its application in the hospital. The calibration factor of the reference chamber was obtained from the Primary Standards Dosimetry Laboratory calibration certificate with its electrometer [16].

Figure 3. Cobalt-60 radiotherapy calibration system at Secondary Standards Dosimetry Laboratory (SSDL) at KEBS, Nairobi, Kenya.

Figure 4. Absorbed dose to water measurement setup in water phantom.

The measurement setup is as shown in **Figure 4** as guided by [17] and [8]. The chambers were placed at reference depth of 5 g/cm^2 in water phantom connected to electrometer at field size of 10 cm × 10 cm. The environmental condition was monitored during the entire period of measurement. The ionization chamber for radiotherapy and National Reference chamber were both exposed to ^{60}Co beam, at a distance of 100 cm from the source, and ten measurement readings taken from the electrometer [18].

The measurement of absorbed dose to water was carried out with the chamber protected by a PMMA sleeve, positioned in a 30 cm × 30 cm × 30 cm water phantom and the reference point on the central axis of the beam. The chamber axis was perpendicular to the central axis of the beam and the distance from the source to the reference point of the chamber is 100 cm. The reference point of the chamber was at 5 cm water depth and the size of the radiation field at the reference plane was 10 cm × 10 cm.

3. Results and Discussion

Air kerma measurement results

Table 1 shows the result of two ionization chambers exposed to cobalt 60 radiation beam, with National Chamber traceable to International System regarded as the reference standards. The measurement was taken in form of charge using ionization chamber connected to electrometer. The accuracy was tabulated according to equation 6 and air kerma was derived according to equation I. The average error for the chamber under investigation was found to be −1.93% taking into consideration the SSDL chamber as the true value. The radiotherapy chamber under test consistently displaying higher reading for all the 10 readings observed.

Table 1. Air kerma measurement comparison results of reference standard and radiotherapy chamber under investigation.

No	National reference standard	Radiotherapy chamber under investigation	Accuracy %
	Air kerma, Gy/sec ± 0.001	Air kerma, Gy/sec ± 0.001	
1	5.247	5.350	1.97
2	5.248	5.347	1.90
3	5.247	5.347	1.92
4	5.247	5.346	1.90
5	5.247	5.347	1.92
6	5.245	5.346	1.92
7	5.245	5.347	1.94
8	5.245	5.347	1.94
9	5.247	5.349	1.94
10	5.245	5.347	1.94
		Average deviation	1.93

Absorbed dose to water measurement results.

Table 2 shows the measurement results for absorbed dose to water for the reference ionization chamber and the radiotherapy chamber under investigation. The absorbed dose to water measurement was obtained by irradiating both the ionization chambers in a cobalt 60 beam, with National Chamber traceable to International System regarded as the reference standards. The measurement was obtained in form of charged and absorbed dose to water derived according to equation IV. The results indicate an average error of the chamber under investigation as −2.12%. The radiotherapy chamber under investigation consistently displaying lower compared to the reference reading for all the 10 readings observed.

Table 2. Absorbed dose to water measurement results of reference ionization chamber in comparison to radiotherapy chamber under investigation.

No	National reference standard	Radiotherapy chamber under investigation	Accuracy %
	Air kerma, Gy/sec ± 0.001	Air kerma, Gy/sec ± 0.001	
1	4.720	4.820	−2.11
2	4.722	4.819	−2.06
3	4.720	4.820	−2.11
4	4.720	4.820	−2.11
5	4.720	4.820	−2.11
6	4.717	4.821	−2.21
7	4.720	4.821	−2.14
8	4.720	4.821	−2.14
9	4.720	4.820	−2.11
10	4.722	4.820	−2.09
		Average	−2.12

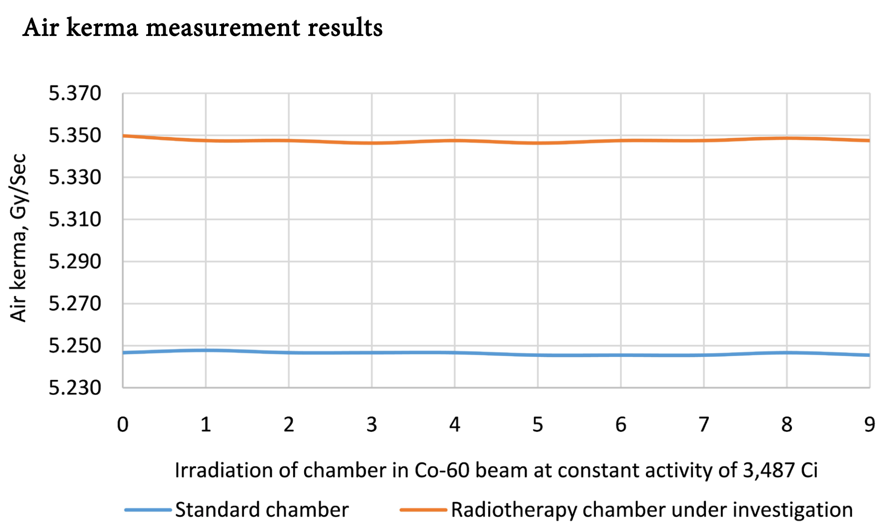

Figure 5. Comparison of air kerma for the reference standard and radiotherapy chamber under investigation.

Figure 5 shows air kerma comparison results for both the reference chamber and the radiotherapy chamber using data from **Table 2**. It was observed that the chamber under investigation consistently showed higher reading in comparison to the reference chamber. During the application, the error of the chamber will automatically be transferred to radiotherapy process, leading to underestimation of dose by −1.93%. Depending on the magnitude of error, such deviation has potential of compromising the prescribed dose. Since radiotherapy involve exposure of ionizing radiation to human, there is need to protect the patient from unnecessary and unintended exposure from incurring high doses. All necessary precaution must be taken so that exposure is carried out with precision and reproducibly.

Absorbed dose to water measurement results.

Figure 6 shows the absorbed dose to water results for both the reference standard chamber and radiotherapy chamber under investigation tabulated with results derived from Table 2. The ionization chamber readings of the chamber under investigation were found to be displaying higher reading consistently in comparison to National Reference. The implication is that if the chamber is used in this condition, then it will automatically transfer underestimated result of radiation dose to the treatment process. An under dosage of about −2.12% at this stage should be avoided because of its potential to compromise the treatment outcome.

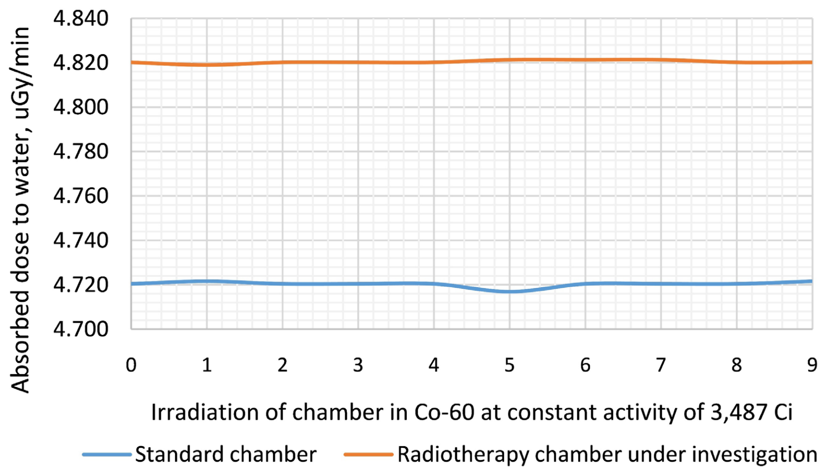

Figure 6. Absorbed dose to water results for both the standard chamber and radiotherapy chamber.

Comparison of air kema and absorbed does to water

From Table 3, the air kerma values was found to be higher than the absorbed dose to water values. An average difference of 11% was found between the two quntities of air kerma and absorbed dose to water. Therefore, during clinical practice, the air kerma values cannot be used for absorbed dose to water.

Table 3. Comparison of air kerma and absorbed dose to water.

No	Average air kerma	Average absorbed dose to water	Accuracy
	Air kerma, Gy/sec	Air kerma, Gy/sec	%
1	5.35	4.82	11

Calibration coefficient results for air kerma and absorbed dose to water.

Table 4 shows the established calibration coefficient results for air kerma and absorbed dose to water, according to Equation (5). The calibration coefficient facilitates the correction of 1.93% error for air kerma and 2.12% absorbed dose to water. The air kerma calibration coefficient was established as 48.2 mGy/nC and absorbed dose to water as 52.98 mGy/nC.

Table 4. Calibration coefficient for air kerma and absorbed dose to water.

No	Quantity	Item	Measured/derived	Units
1	Air kerma Calibration coefficient, N_k	Average charge measurement	0.000000004492	C/30 min
		Air kerma rate	0.00872	Gy/Sec
		N_k from the reference certificate	49,040,000	Gy/C
		Calibration coefficient, N_k	48.22	mGy/nC
2	Absorbed dose to water Calibration coefficient, N_D	Average charge measurement	0.000000004033	C/30 min
		Absorbed dose to water rate	0.008595	Gy/Sec
		N_D from the certificate of reference	53,800,000	Gy/C
		Calibration coefficient, N_D	52.98	mGy/nC

The established calibration factor facilitates the correction of the results of radiation detector to provide correction of readings. Calibration factor is significant in regard to optimization and improvement of treatment outcome, by compensating for errors associated with the chamber under investigation. This is an important step for increasing the accuracy level of the radiotherapy treatment. The calibration factor enforces quantitative relationship between National Reference dosimetry performance and the clinical chamber under investigation, as indicated in Equation (5).

There were several limitations encountered during the investigation, including lack of access of historical long-term data, maintenance records, and quality assurance programmes. Further to this, the effect of dust was not taken into consideration during analysis because of lack of measuring equipment. An assumption was also made that the acceptance tests and commissioning values were the same as the original values during commissioning. During analysis C0-60 was assumed to be a point source for quantitative dose determination.

4. Conclusion

The study demonstrates and establishes that radiotherapy beam determination is prone to errors, for both air kerma and absorbed dose to water. The accuracy capability for radiotherapy equipment under investigation was off by −1.93% and −2.12% for air kerma and absorbed dose to water in comparison to the National Reference standard. The treatment outcome is dependent on the accuracy of dose delivery to the tumor. Hence there is a need to independently verify the accuracy of radiation dose to ensure precision of dose delivery. The investigation entrenched that the accuracy level can be improved by incorporating calibration coefficient to compensate for the error associated with the clinical equipment to achieve optimum treatment. The calibration factor provides mechanism for accounting of error in the treatment process. In this case, the $N_{D,W}$ was determined as 52.9 mGy/nC. This methodology provides enough room for achieving ±5% dose delivery to tumor target as recommended by ICRP 2007 for good clinical outcome.

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Conflicts of Interest

There was no conflict of interest in this study.

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