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The Calibration and Use of a New Ring-Shaped Ionization Chamber for Monitoring and Dosimetry of X-Ray Beams

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Abstract

Today, dosimeters are used generally for dosimetry of the diagnostic X-ray beam. Ionization chambers are appropriate instruments for monitoring and also the dosimetry of X-ray beam in medical diagnostic equipment. The present work introduces design and investigation of a new ring-shaped monitor chamber with a PMMA body, graphite-coated PMMA windows (0.5 mm thick), a special graphite-foil central electrode (0.1 mm thick, 0.7 g/cm^3 dense) that creating two sensitive volumes and a central hole for crossing the radiation beam with less attenuation. The results of performance tests conducted at the Nuclear Science and Technology Research Institute, AEOI in Karaj-Iran proved the high short and long-term stability, the very low leakage current, the low directional dependence and very high ion collection efficiency through the special design of the collecting electrode. Moreover, the FLUKA Monte Carlo simulations certified the negligible effect of central electrode on this new ring-shaped monitor chamber. According to the results of the performance tests, the new monitor chamber can be used as a standard dosimeter in order to monitor X-ray beam in primary standard dosimetry laboratories.

Keywords

Ring-Shaped Monitor Chamber, Diagnostic X-Ray Beam, Quality Control Tests, Low Dens Graphite-Foil, Central Electrode

1. Introduction

There are various methods for measuring the intensity and energy of radiation beams. Ionization chambers are

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widely used for dosimetry and measuring the absorbed dose of ionizing radiation [1]. In this type of dosimeters, the gaseous ionization method used for dosimetry of radiation beams [2]. High accuracy, suitable response and simplicity of the design are some of the features of this type of detectors [3] [4].

One particular type of ionization chamber is ring-shaped monitor chamber with a central hole for crossing the radiation beam with less attenuation. These dosimeters are the suitable devices for measuring the diagnostic X-ray beams. Due to the central hole of the geometry of ionization chamber, the dose delivery is provided without attenuation, especially in diagnostic range of the ionizing radiation [5].

The following plan explains the design and fabrication of an improved ring-shaped monitor chamber that consists of two volumes of gas trapped between two entrance windows and separated by a special graphite-foil central electrode and a central hole for crossing the radiation beam. The presence of two sensitive volumes will lead to increase the ion collection efficiency and improved response, relative to existing ring-shaped monitor chamber designs. A series of standard were performed with radiation therapy units, X-rays and check sources at the Nuclear Science and Technology Research Institute, AEOI in Karaj-Iran to assess the reliability of the design. The results of the quality control tests confirm that the dosimeter is suitable for standard reference use in Primary Standard Dosimetry Laboratory (PSDL) units and for dosimetry of diagnostic X-ray beams. In addition, the FLUKA Monte Carlo studies provide useful information regarding energy deposition in the chamber's sensitive volumes and also the very low effect of the detector's materials on the response of the device.

2. Materials and Methods

As seen in **Figure 1**, this new ring-shaped monitor chamber contains a body made of PMMA, two entrance windows made of a 0.5 mm thick layer of PMMA coated by graphite, a collecting electrode made of a special thin graphite foil with a thickness of 0.1 mm and a central hole for crossing the radiation beam.

In order to make a more uniform electric field in edges and limit the sensitive volume of gas, the collecting electrode should be surrounded by a guard electrode having a width not smaller than 1.5 times the cavity height. Embedded guard ring leads to reduce the leakage current significantly [2]. Technical information of the ring-

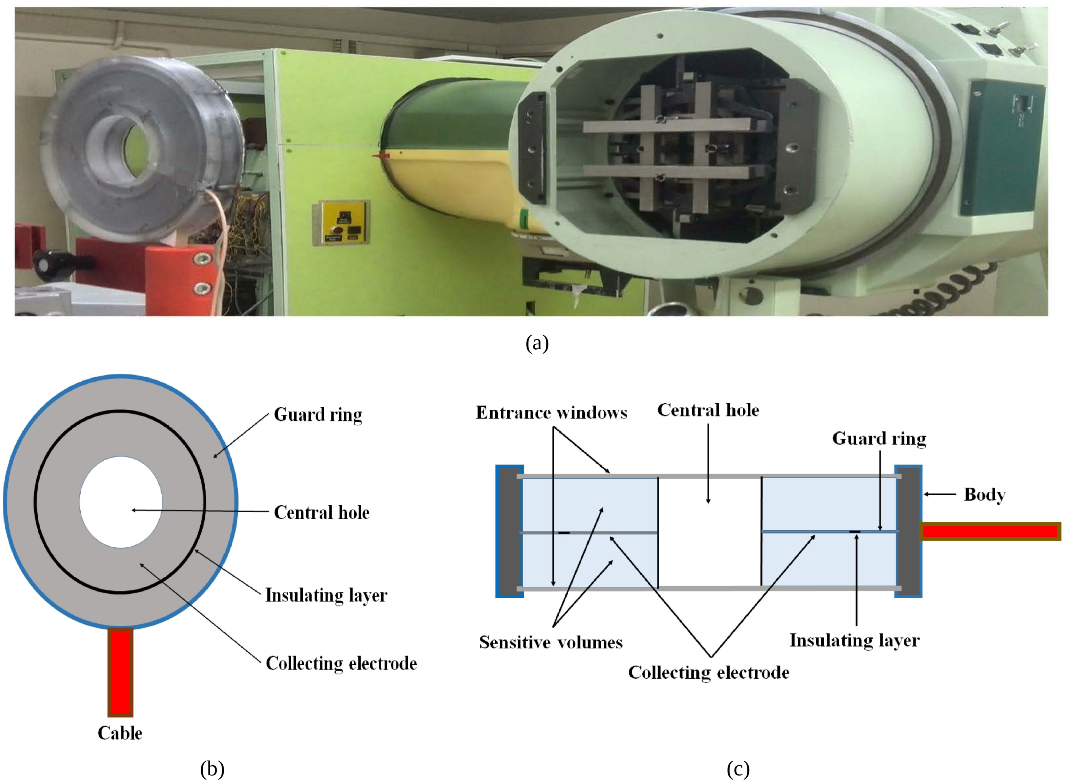

Figure 1. (a) A photo of new ring-shaped monitor chamber under Picker V9 radiation therapy unit; (b) Schematic of central electrode and (c) Body geometry.

shaped monitor chamber is indicated in **Table 1**. It should be mentioned that the presence of dust or any spots on the electrodes can lead to an increase in leakage and also errors in the response.

To apply high voltage into electrodes and collect the ionization charge, a coaxial cable, BNC and BANANA connector is used. To conduct tests, a PTW electrometer model UNIDOSE E2670 were used to measure ionization and produce high voltage. To perform the quality control and calibration tests, a Picker V9 and Theratron 780c radiotherapy unit, ^{90}Sr check sourse and a Siemens model diagnostic range X-ray generator device were used.

3. Results and Discussion

The performance of the ring-shaped monitor chamber with two sensitive volumes, and the specific arrangement of the electrodes was evaluated and calculated in the standard laboratory by measuring the effect of polarity and obtaining the saturation curve, by determining the amount of leakage current, and by conducting tests for stability, linearity of response, directional dependence and energy dependence. Additionally, the results of energy deposition in sensitive volumes by FLUKA Monte Carlo simulation have been discussed.

3.1. Saturation Curve, Ion Recombination Factor and Polarity Effect

To determine the best range of operating voltage, ring-shaped monitor chamber saturation curves are plotted. To perform this test, the Siemens diagnostic rang X-ray generator is placed at SSD = 30 cm from the ring-shaped monitor chamber (in this position, the air-kerma rate was 544.2 mGy/min). The obtained value of the ionization flow is calculated in different applied voltages from −400 V to +400 V in increments of 50V. It should be noted that the adjusted ionization results are calculated based on the following equation [6]:

$$I_{\text{ionization}} = K_{TP} \cdot I_{\text{read}}\left(nC\right); K_{TP} = \frac{273.16+T}{293.16} \times \frac{1013.25}{P} \tag{1}$$

where T & P are the temperature and pressure of ionization chamber respective.

As seen in to **Figure 2**, the ring-shaped monitor chamber response is almost identical regardless of the voltage applied. To conduct the tests, the best-selected voltage is 400 volts. According to **Figure 2**, the polarity effect of voltage and the ion collection efficiency can be calculated.

To calculate the polarity effect according to the following equation [7], compare the resulting ionization charge collected by the ion chamber between two symmetric voltages (for example, +50 V and −50 V):

$$K_{pol} = \frac{|M_+| + |M_-|}{2 \cdot M} \tag{2}$$

In relation 2 M_+ and M_- are the chamber signals obtained under identical irradiation conditions at positive and negative chamber polarities, respectively, and M is the signal obtained at the polarity used routinely (either posi-

Table 1. Technical information of the new ring-shaped monitor chamber.

Features	Properties
Total chamber volume (cm^3)	271.43
Air sensitive volume (cm^3)	207.34
Graphite foil density (g/cm^3)	0.7
Entrance window (PMMA graphite coated) thickness (mm)	0.5
Central electrode (Graphite foil) thickness (mm)	0.1
Central electrode diameter (mm)	180
Collecting electrode diameter (mm)	160
Central hole diameter (mm)	60
Outer diameter (mm)	200

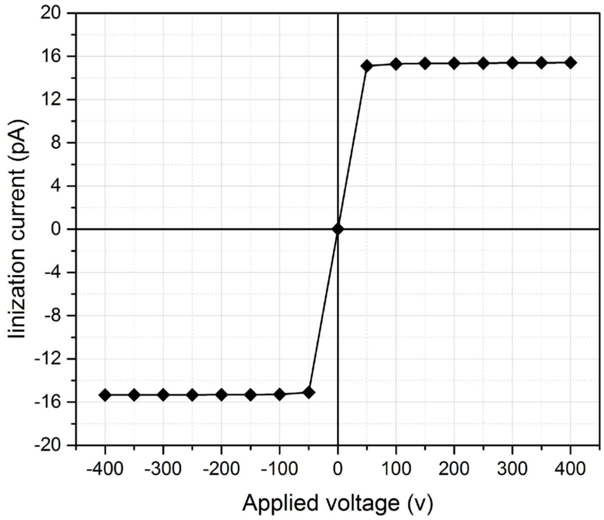

Figure 2. Saturation curve of the ring-shaped monitor chamber using diagnostic range X-ray beam.

tive or negative). Based on the recommended Standard, the Polarity effect on the ratio of the amount collected should not be more than 1% [8]. In this new ring-shaped monitor chamber, the maximum amount of polarity effect (in voltage ±50 V) was approximately 0.11%. If the applied voltage in the ring-shaped monitor chamber is not appropriate, before being collected by the collecting electrodes, it is possible that the ions will recombine.

The ion collecting efficiency, for the continuous beam is calculated based on the following equation [7]:

$$K_{sat} = \frac{\left(\frac{V_1}{V_2}\right)^2 - 1}{\left(\frac{V_1}{V_2}\right)^2 - \frac{M_1}{M_2}} \tag{3}$$

In relation 3 M_1 and M_2 is the charge collected by the ionization chamber in voltage V_1 and V_2 respectively and where $V_1/V_2 = 2$. According to the recommended standard [8], the ion collection efficiency should be greater than 99%, which in this new ring-shaped monitor chamber, the ion collection efficiency, is greater than 99.94%. Therefore, the amount of ion recombination factor for this monitor chamber is 1.0008.

3.2. Leakage Current

Based on the proposed standard, the leakage current should be less than 5% of the ionization current produced at the minimum effective air-kerma rate [9]. In other words, according to the standard, within 5 sec after the end of a 10 min irradiation, the leakage current shall have decreased to ±1.0% or less of the ionization current produced in the measuring volume during the irradiation [8].

Due to the reduced resistance of the used insulators between the electrodes of this ring-shaped monitor chamber during the irradiation, the current leakage increases; this can combine with the ionization process and cause errors in measurements. In this case, the amount of leakage current, after the cessation of irradiation, in a small period of time, reaches 1% of the main current produced during irradiation. So the leakage current is negligible.

In the current monitor chamber with an operating voltage of 400 volts without irradiation, the measured leakage current is about 1.1×10^{-16} A. Within 5 sec after the end of several minutes irradiation by Picker V9 radiotherapy unit, the leakage current decreased to 0.402% of the ionization current produced by the new monitor chamber. Similar results are seen when the test is repeated, which is an indicator that there is a low leakage in the new ring-shaped monitor chamber.

In addition to the mentioned methods, for measuring the leakage current using ^{90}Sr check source, the ^{90}Sr source is placed on the entrance window and after collecting 1nC charge by this ionization chamber, the ^{90}Sr source is removed. The leakage current decreased to 0.37% of the ionization current after 3 seconds.

3.3. Short-Term Stability

In short-term stability test, the new ring-shaped monitor chamber is irradiated 10 times using Picker V9 radiotherapy machine. After reaching a stabilized state, within10-second intervals, the amount of collected charge will be measured. After stopping the irradiation and spending a few minutes, the same process will be repeated generally in ten trials. According to the recommended standard, the limit of variation should be less than ±0.3% [8]. As shown in **Figure 3**, the maximum variance resulted from this new ring-shaped monitor chamber measured in several times, is approximately 0.104%.

3.4. Long-Term Stability Test

In the long-term sustainability based on the proposed standard, the limit of variance of current difference output by the stability check device shall not be greater than ±0.5% over one year [8]. In this monitor chamber, during a five months trial period, with specific intervals, the maximum variation observed was less than 0.347% (**Figure 4**).

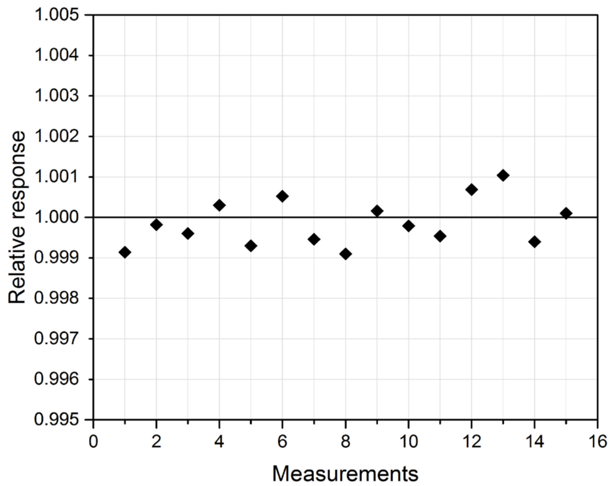

Figure 3. Short term stability result of new monitor chamber using Picker V9 radiotherapy unit.

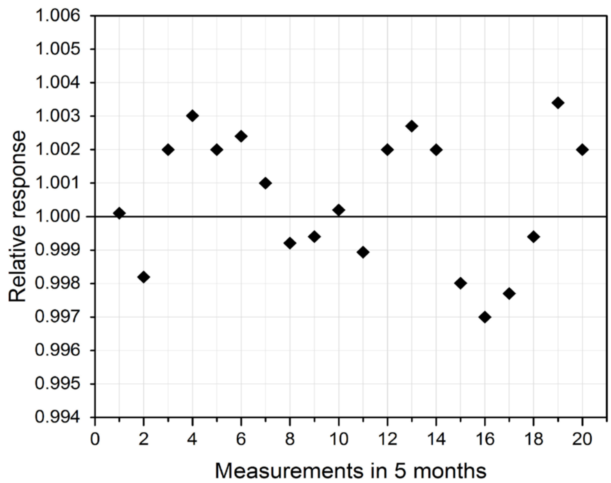

Figure 4. Long term stability result of new monitor chamber using Picker V9 radiotherapy unit.

3.5. Linearity of Response Based on Various Air-Kerma Rate

In linearity of response test, the ring-shaped monitor chamber is irradiated by Picker V9 radiotherapy unit at various distances from SSD = 160 cm to SSD = 70 cm, and the ionization current is calculated according to equation (1). **Figure 5**, plots the collected charge versus the air-kerma rate in various SSDs. According to the **Figure 5**, the new monitor chamber has a linear behavior with a correlation coefficient of 1.000. The calibration coefficient is calculated according to following equation [7]:

$$N_k = \frac{\dot{K}_{\text{air},\,^{60}\text{Co}}}{I_{\text{read}} \times K_{TP}} \left(\text{Gy}\cdot\text{C}^{-1}\right) \quad (4)$$

The calibration coefficient for this new ring-shaped monitor chamber (with field size equal to 10 × 10 cm^2) is 0.238 ± 0.011 (×10^6 Gy·C^{-1}).

3.6. Directional Dependence

In directional dependence test, the new ring shaped chamber was irradiated by Theratron 780c radiotherapy unit at various angles from 0 to 360 degrees (In each stage of this prosses the 10 degrees are added). The responses were normalized to the reference position (0 degree). Based on the recomende standard, the limit of variation following tilting of the radiation by ±5 degrees, should be less than 1% [9]. According to the **Figure 6**, the diviation of relative response following tilting of the chamber by up to ±10 degrees was less than ±1.0%. Furethermore, according to the **Figure 6**, the result of the test shows that the new ring-shaped monitor chamber has the same response when irradiated on either side.

3.7. Energy Dependence and Energy Deposition

The result of energy dependence was obtained by comparing the measurements with the PTW monitor ionization chamber data, type 34,014 [10]. According to **Figure 7**, the results of energy dependence for this new ring-shaped monitor chamber irradiated by Siemens Stabilipan X-ray unit, shows that this new monitor chamber has a suitable response in diagnostic range of X-rays.

To evaluate the effect of central electrode on the ion chamber response, a FLUKA Monte Carlo simulation was conducted. The results of simulation showed the negligible effect of central electrode on the ionization chamber measurements (the energy deposited in two sensitive volumes were 50.4% and 49.6%).

Using special graphite foil to produce electrode connections (central electrodes and connections of the same material using no metal) leads to a negligible secondary electron flounce in sensitive volumes and also improves the performance of ring-shaped monitor chamber compared with conventional ones.

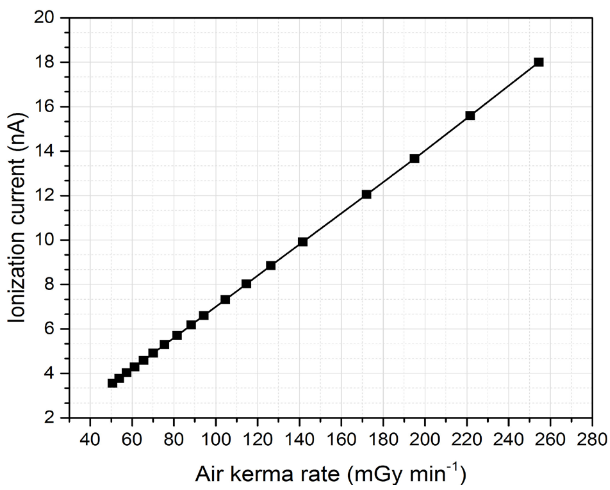

Figure 5. Results of linearity test based on various air-kerma rate.

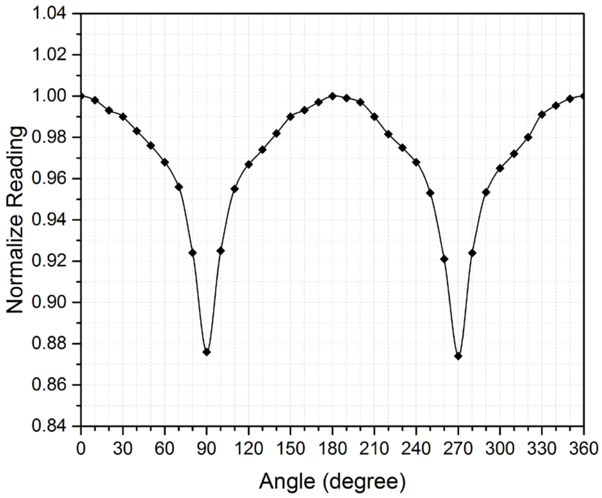

Figure 6. Result of directional dependence using the ratron 780 c radiotherapy unit.

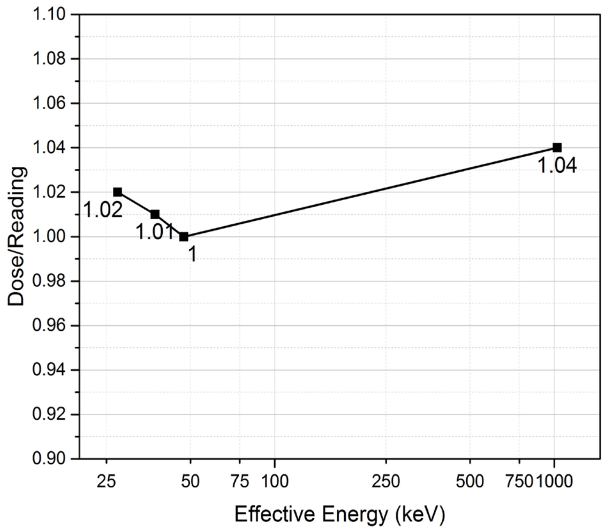

Figure 7. Energy dependence of the new ring-shaped monitor chamber normalized to the photon energy of 47.3 keV.

4. Conclusions

In the present work, the fabrication and performance tests of a new ring-shaped monitor chamber with two sensitive volumes were evaluated. The results of tests in compared with the recommended standards showed the appropriate response of this monitor chamber. Additionally, the result of energy dependence shows that this product has a suitable response in diagnostic X-ray range.

The results of Monte Carlo simulations reveal that using a special graphite-foil with low density and thickness for the production of central electrode has a negligible effect on the monitor chamber response as compared to the conventional ring-shaped monitor chambers with one sensitive volume aluminized polyester foil entrance window and PMMA coated by graphite central electrodes. Based on the result of tests, the presence of two sensitive volumes will lead to increase the ion collection efficiency. And also a homogeneous construction of the collecting electrode, guard ring, and electrode connections results in very low secondary-electron flux, which leads to an upgrade in the performance of this ring-shaped monitor chamber. The results of quality control tests confirm the usefulness of this new ring-shaped monitor chamber for monitoring and also dosimetry of diagnostic X-ray beams in PSDL units.

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