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Experimental Validation of Small-field Dosimetry in Radiotherapy Using Ionization Chamber and Edge Detector

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ABSTRACT

Introduction: Recently, modern radiotherapy techniques have been extensively developed to deliver doses only to therapeutic volume. The objective of the present study was to empirically evaluate the performance capability of the ionization chamber in comparison to the edge detector.

Material and Methods: Firstly, the performance of the ionization chamber, compared to that of the edge diode detector, was validated at a 10×10 cm^2 field size. Then, the percentage depth dose (PDD), percentage surface dose, and transverse profile doses at the 2×2, 3×3, and 4×4 cm^2 field sizes were evaluated for both dosimeters. The empirical and statistical results in a water phantom were compared to those reported for the edge diode detector as the reference field dosimeter using the 6 MV Elekta linear accelerator.

Results: The empirical and statistical results of the transverse profiles of the ionization chamber and edge detector are in agreement for the reference field of 10×10 cm^2. However, a small difference between the two dosimeters could be observed in small fields. A discrepancy of less than 1% was observed between the results of PDDs for two dosimeters in small fields.

Conclusion: The dosimetric characteristics of the ionization chamber and edge detector illustrated some differences, especially in terms of transverse profiles at the small-field size. This discrepancy could be related to the volume effect of the chamber which affects the penumbra. Due to the importance of sensitive organs, it is recommended to utilize the ionization chamber for small radiotherapy fields.

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Introduction

In radiation therapy, a precise dose of high-energy radiation, mainly X-ray, is used for the treatment of cancerous cells; accordingly, normal tissue receives the minimum dose. Radiotherapy is implemented to treat a variety of malignant cells, such as solid tumors. The absorbed dose damages cancerous cells and prevents their cell proliferation [1]. In order to design a treatment plan and achieve maximum efficiency (i.e., the maximum dose absorbed in the tumor and minimum dose in normal tissues), the knowledge of dose distribution and percentage depth dose (PDD) in tissue (phantom) has a great importance [2].

Small fields are usually attributed to the therapeutic field sizes which are between 4×4 and 0.3×0.3 cm^2 [3, 4]. Although both large and small fields are important from a therapeutic point of view, in some cases, in the presence of organs at risk located inside the volume of treatment, small therapeutic fields have more importance, especially in head and neck tumors [5]. However, the effects of scattering radiation from the collimators are more important in small fields. The small field is also used in intensity-modulated radiotherapy as small segments and stereotactic radiosurgery method [6]. Low energy scattered radiation at the edges of radiation fields could be regarded as one of the important factors in the dosimetry and implies the therapeutic role in all fields.

Duo to the increase in scattering radiation, it has much less effect on the PDD in small fields, compared to that reported for larger fields. Due to the higher sensitivity to low dose detection, the utilization of silicon diodes is recommended for the small-field dosimetry. Moreover, the penumbra effect is an important factor at the edge of the therapeutic fields. This effect is expected to be as low as possible in order to have more accurate dosimetry of such fields [7].

Generally, the ionization chamber (i.e., Semiflex) is composed of a gas-filled cavity surrounded by an external wall and a central collecting electrode. For the minimization of the photon escape, the wall and collector are separated by high-quality insulation [8]. On the other hand, the edge detector consists of very small and highly sensitive silicon. The size of such a detector facilitates the precise measurements of the dosimetric parameters in small radiation fields [9]. It is also very accurate in the measurement of the beam

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edges, as well as the full beam produced by the accelerator.

Several reasons could be pointed for the superiority of the edge detector over the ionization chamber. Among them is the higher density of the sensitive volume which results in the more charge carriers and lower probability of photon escape in the edge detector. Therefore, the edge detector has higher efficiency, compared to the ionization chamber, especially in the case of high energy photons [10, 11]. Due to the dosimetric importance of small therapeutic fields, the current study investigated an empirical validation of the ionization chamber (i.e., Semiflex) in comparison to the edge diode detector as the reference dosimeter.

The importance of small therapeutic fields leads to performing several studied with the aim of the related dosimetry tools, methods, and accuracy of the outputs. Cheng et al. studied the dose linearity, dose rate dependence, PDD, output factor, as well as beam profiles for 6 MV photon beams at different field sizes and therapeutic field depths. They compared the results of the edge detector with those reported for a standard volume ionization chamber and photon diode detector [9].

A study was conducted by Shin et al. [12] for the evaluation of the profiles, PDDs, and relative output factors of a Novalis 6-MV SRS beam. The edge diode detector, diode detector, and ion chamber were used in small fields in a water phantom. The ionization chamber was not utilized for measurement in the two aforementioned studies. A dosimetric study was carried out by Lu et al. based on the output ratios to assess the polarity effect at different small-field sizes [13]. Five different ionization chambers, including Semiflex, PinPoint, and Razor were used; however, the edge detector was not used in the aforementioned study. Groppo et al. used film detectors to measure the beam profiles for electa SRS cone collimators. The penumbra width was calculated for each cone size in each profile. Their results corroborated the expected values of penumbra for the elekta stereotactic cone collimation system, as well as suggested through other studies and detectors [14]. The exradin W1 plastic scintillator detector was utilized for small field measurments. They obtained TPR measurements had standard deviations (SD) < 1%; SD < 0.4 mm for the profile penumbra and suggested this detector for small field measurements [15]. The influence of detector size relative to field size in small-field photon beam were examined through synthetic diamond detectors of various types and sizes. The results showed that with careful selection of a suitable crystal type of a given size and orientation, the relative dose measured with the diamond probe would agree favorably within 72% with that measured with a small-field detector [16].

There are several reasons to perform this type of study. Firstly, there is no agreement between the researchers on the use of a specific type of dosimeter in small-field dosimetry. Secondly, the dosimetric validation of the ionization chamber in comparison to the edge detector, as a reference in the small fields, was not evaluated in any of the previous studies. Therefore, the current study aimed to evaluate the dosimetric capability of the ionization chamber (i.e., Semiflex) in a water phantom for the small fields of 2×2, 3×3, and 4×4 cm^2 using 6 MV X-ray beams.

The field size of 10×10 cm^2 was utilized as the reference field. The dosimetric parameters of the ionization chamber, such as the PDDs, percentage surface dose, and transverse profiles, were compared to those of the edge detector as the reference dosimeter. The obtained results promised the utilization of the ionization chamber as an alternative dosimeter in the small-field radiotherapy.

Materials and Methods

The experimental procedure was performed in Omid Hospital, Mashhad University of Medical Sciences, Iran, in 2019. The Elekta linear accelerator AU036 (Elekta, China) which produces 6 MV X-ray beams was used in the experiments of the present study. The Elekta is suited for the treatment of the breast, as well as head and neck cancers. Water phantoms are used for relative dosimetry in radiotherapy and are capable of accurate dosimetry for most tests. In this study, 3D SCANNER™ (Sun Nuclear, USA) was utilized in the experimental setup. It has a cylindrical reservoir that permits three-dimensional (3D) dosimetry. The self-adjusting feature of the phantom provided both more accurate measurements and less startup time. The data were obtained using the 3D scanner (Sun Nuclear Corporation, Melbourne, USA).

The ionization chamber (Semiflex-TN31010, PTW, Germany) was chosen for the study which was manufactured by PTW company. Semiflex is one of the most widely used and efficient chambers in the case of relative dosimetry. The waterproof feature of Semiflex permits to control the basic parameters of the water phantom. It has a sensitive volume of 0.125 cm^3. The edge detector (Sun Nuclear, USA) equipped by radiation resident silicon, was an active detecting element in the setup. The element had an area of 0.8×0.8 cm^2 housed in brass and located parallel to the upper surface of the detector. The physical characteristics of the utilized dosimeters are summarized in Table 1. Figure 1 depicts the ionization chamber and edge detector used in the experimental setup of the current study. The location of the ionization chamber and edge detector are shown in figures 2a and 2b, respectively.

The linear accelerator was calibrated and verified by the Atomic Energy Organization of Iran. The edge detector and ion chamber were calibrated and verified by Karaj Secondary Standard Dosimetry Laboratory in Iran. After the calibration and performance of the system was checked, the accelerator was set at the 0º of the gantry angle and 0º of collimator angle with the maximum field of 4×4 cm^2.

Table 1. Physical characteristics of detectors

Detector	Sensitive material	Inner electrode	Sensitive volume (mm^3)	Dimension	Package material
Semiflex (PTW-31010)	Air	Aluminum	125	5.5 mm diameter, 6.5 mm length	Acrylic and graphite
EDGE (Sun Nuclear)	Silicon	-	0.019	0.8 mm length, 0.03 mm thickness	Brass

(a) (b)

Figure 1. Employed (a) ionization chamber (Semiflex) and (b) edge detector in this study

(a) (b) (c)

Figure 2. (a) Ionization chamber (Semiflex); (b) edge detector located on water phantom; (c) placement of phantom

As shown in Figure 2c, the bed is rotated, and the water phantom is properly adjusted under the linear accelerator head. Then, the reservoir was filled. Firstly, the phantom level, voltage dosimeters, monitor unit, and other parameters were checked by the software control unit, and afterward, the experiment started.

The edge detectors can be produced at a small size due to their high density of sensitive volume. As a result, there are more charge carriers and less probability of photon escape in the edge detector; therefore, the edge detector has a higher efficiency, compared to the ionization chamber, especially in the case of high energy photons. Due to the increasing cross-section of the photoelectric effect in semiconductors, these detectors overrespond to the photons of low energy. Consequently, the edge detectors usually have metallic shields for the attenuation of low-energy photons [17].

On the other hand, in the ionization chamber, the main interaction of the photon with the matter in low-energy ranges is the photoelectric effect which leads to the electron equilibrium. To achieve the electron equilibrium condition in the wall of the ionization chamber, the wall thickness should increase with increasing photon energy. However, to minimize the photon attenuation in the wall, the thickness should be usually optimized in higher energies. This is the reason the manufacturing company generally considers the specification of the ionization chamber for higher photon energy. Other important parameters are the atomic number, as well as the placement and dimension of the anode [18].

Results

The PDDs and transverse profiles were obtained by the data from the dosimetric results measured by the edge detector and ion chamber in the field sizes of 4×4, 3×3, 2×2, and 10×10 cm^2, respectively. Due to the maximum resolution at the energy of 6 MV, transverse profiles were measured at the depth of 1.5 cm. Figure 3 illustrates the PDD measurements at the depths of 10 and 20 cm from the phantom surface for both dosimeters and all field sizes. As shown in the figure, with the reduction of the field size, the PDD decreases.

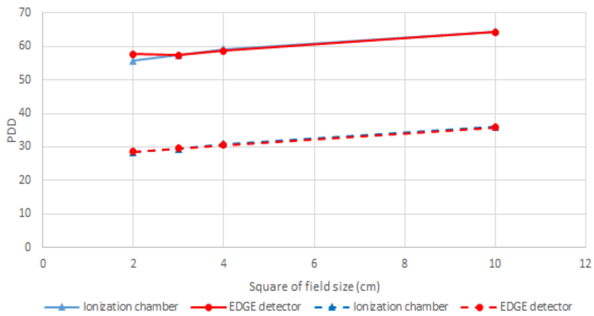

Figure 3. Results of percentage depth dose for both dosimeters; solid lines: at depth of 10 cm from the phantom surface; dashed lines: at depth of 20 cm from the phantom surface

Moreover, there were no significant deviations between the two dosimeters for all field sizes. The relative difference between the results of the PDDs at two different depths (i.e., 10 and 20 cm) was less than 1% for all field sizes. For example, the minimum value of the relative difference was 0.07% for the case of 2×2 cm^2 field size at 10 cm depth. Another important parameter was the percentage surface dose. The variation results of the PDD at the surface in terms of field size for both detectors are shown in Figure 4. Generally, the percentage dose at the surface was dependent on the size of the therapeutic field. It can be observed that with increasing the field size, the percentage surface dose also increases. This behavior could be related to scattering radiation and similar for both dosimeters.

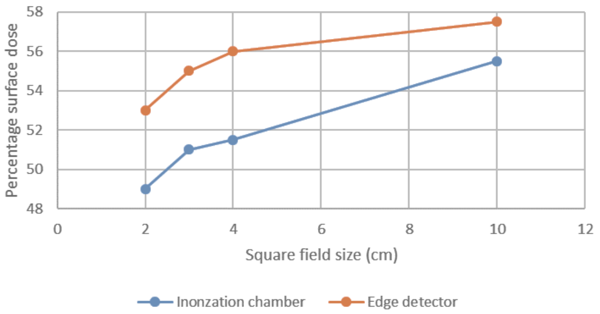

Figure 4. Results of percentage surface dose for both dosimeters

Figure 5 depicts the results of the transverse profiles. As shown in Figure 5, there is an agreement between the two dosimetry approaches for the reference field size of 10×10 cm^2. Moreover, a small difference between dosimeters could be observed with decreasing the therapeutic field size. This behavior could be due to the volume effect of the chamber which affects the penumbra. The dose gradient was not in the electron equilibrium state and resulted in the penumbral region.

On the other hand, according to the Bragg hole theory, electron equilibrium conditions, and discrepancy of these conditions in small fields, there is uncertainty in dosimetric results. Therefore, dosimetric results are influenced by dosimeter selection and design, which is a serious challenge in clinical applications. The penumbra region is generally defined as the lateral distance between 20% and 80% of isodose lines [19]. The variation of penumbra width in terms of field size at a depth of 1.5 cm is depicted in Figure 6 for both dosimeters. It can be observed that with increasing the field size, the penumbra width also increases in two dosimeters.

In order to present a more quantitative analysis of the transverse profiles for the field sizes of 10×10 (i.e., the reference field), 4×4, 3×3, and 2×2 cm^2 (i.e., small fields), one-sample tests were conducted using SPSS software (25).

The obtained two-tailed p-value was 0.000 (less than 0.05) which indicated that the mean of the variable was different from 0. Therefore, it was confirmed that the mean difference was different from the test value. The obtained mean differences for both dosimeters were equal to 0.06, 0.23, 0.17, and 0.63 for 10×10, 4×4, 3×3, and 2×2 cm^2, respectively.

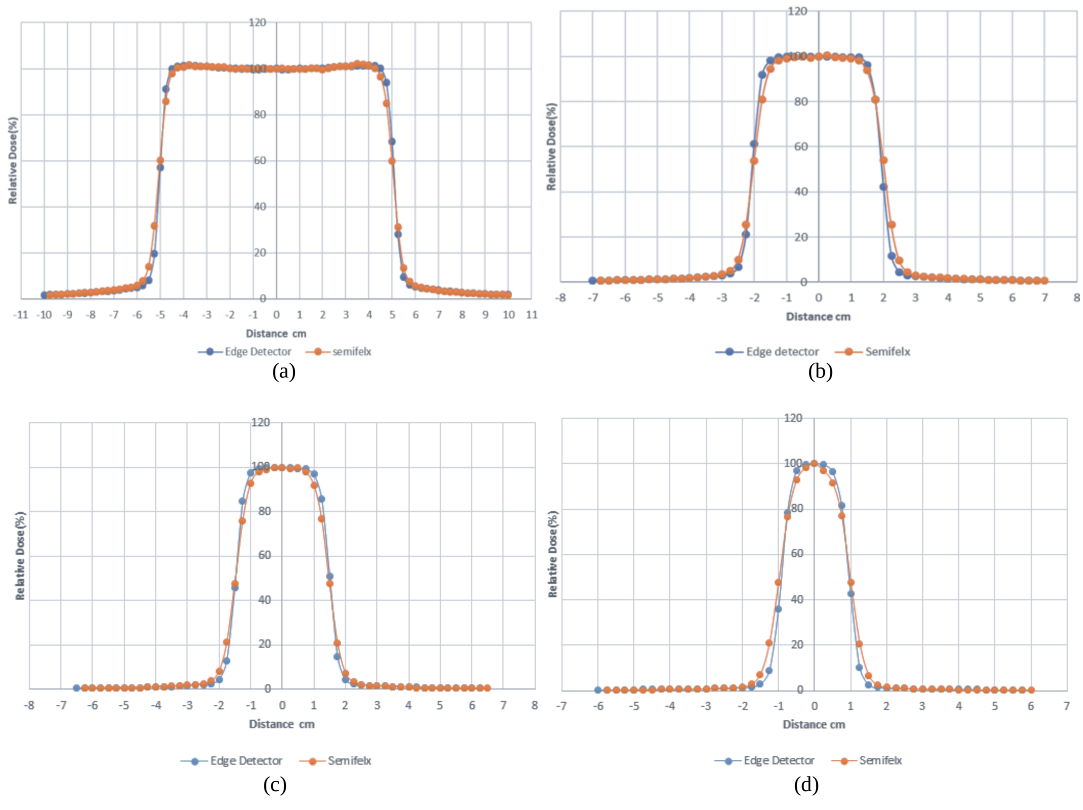

Figure 5. Transverse results of ionization chamber and edge detector for field sizes of (a) 10×10 cm^2, (b) 4×4 cm^2, (c) 3×3 cm^2, and (d) 2×2 cm^2

A comparison between the results showed that there was a very small difference between the transverse profiles of the ionization chamber and edge detector. The obtained results could corroborate the ionization chamber as an alternative dosimeter for clinical applications.

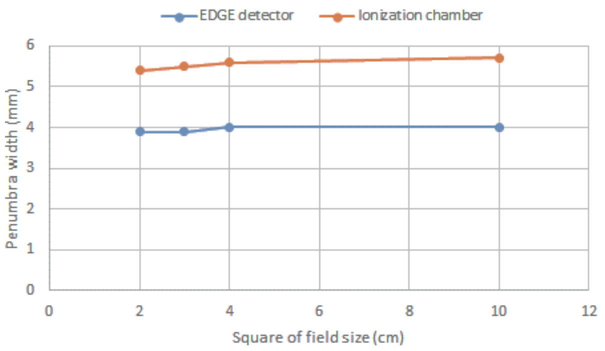

Figure 6. Results of penumbra width for two dosimeters at depth of 1.5 cm

Discussion

Although the edge detector is usually employed in small-field radiotherapy, the ionization chamber is more available in radiotherapy clinics. The edge detectors can be produced at a small size due to their high sensitivity per volume. These detectors have been widely used in small-field dosimetry due to their real-time readout, high spatial resolution, and small size. Due to very good dose response, dose rate independence, and low directional dependence, ionization chambers are widely utilized in radiotherapy.

On the other hand, the limitation of this type of detector occurs when the irradiated field is smaller than the size of the detector. In other words, the application of these dosimeters is limited in small-field radiotherapy. The lack of lateral electronic equilibrium effects is also another limitation parameter. Obviously, in very small fields, an underestimation in response occurs with increasing the active volume chamber in the penumbra region.

To the best of our knowledge, this is the first study that experimentally focused and comprised the performance of ionization chamber and edge detector for small field measurements. Regarding to discrepancy of the obtained results the current results are compatible with the previous studies as mentioned before. The present study indicated that the emphasis of the International Atomic Energy Agency guidelines, as well as the associations, such as the American Association of Physicists in Medicine, on the use of specific ionization chambers for the small-field radiotherapy is mandatory. The reason for this is that the chamber volume negatively affects the dosimetric measurements in such field sizes. Regarding the significant importance of small-field dosimetry in patient radiotherapy and its serious side effects in the case of discrepancies between the calculated and actual dose distributions, the use of small ionization chambers for dosimetry purposes should be on the agenda.

From this point of view, the empirical and statistical analyses in the present study showed a good agreement between the dosimetric performances of the ionization chamber and edge detector (as a reference detector) for the small-field dosimetry. However, from the perspective of the current study, it is suggested to carry out further measurements and comparisons of other output parameters in a humanlike phantom.

Conclusion

The objective of the present study was to empirically evaluate the dosimetric performance of the ionization chamber in comparison to that reported for the edge detector as the reference dosimeter in small-field radiotherapy. The dosimetric parameters, including the PDD, percentage surface dose, and transverse profiles, were investigated for the field size of 10×10 cm^2 as the reference field and small fields of 4×4, 3×3, and 2×2 cm^2 for both detectors.

The measurements were conducted in a water phantom using 6 MV X-ray beams. The empirical and statistical analyses of the present study showed that a reasonable agreement could be observed between the dosimetric performance of the ionization chamber, compared to that reported for the edge detector in small-field radiotherapy. However, in order to minimize the discrepancies between the calculated and actual dose distributions in small-field radiotherapy, it is recommended to carry out further measurements in a humanlike phantom.

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