Study of detectors response on the scatter radiation of 6 MV flattening filter free beams

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Abstract. Small field dosimetry which related to the use of Flattening Filter Free (FFF) beams is a great challenge because of the perturbation effects caused by the size of the detector’s active volume or detector’s materials. This phenomenon encourages researchers to do a further study about detector response. In this study, scatter and primary radiation from 6 MV FFF photon beams were studied to evaluate the detector response in small fields for a better understanding of the contribution of every phenomenon. Ion chamber and Gafchromic films were used in three measurement configurations representing open field measurement and approximations of both primary and scatter part of the beam, described as follows: (i) detectors positioned under steel block, exposing the detectors only to scatter part of radiation field, (ii) detectors positioned inside mini phantom, approximating the detector response to primary radiation with minimum scatter, (iii) detectors positioned in the standard open field, which was the superposition of the primary and scatter radiation. The results show that detector responses were heavily depended on its design (i.e. active volume) especially in small beams. The detector response in the open field could be reproduced from the blocked and primary beam set-up with a discrepancy ranging from 1.0% to 36%. Moreover, the volume averaging and other phenomenon affecting the detector response could be observed in the blocked beam.

1. Introduction

The use of advanced radiation therapy, such as Intensity Modulated Radiotherapy (IMRT), Stereotactic Body Radiotherapy (SBRT) and Stereotactic Radiotherapy (SRT), encourages the use of flattening filter free (FFF) beams. There are many publications explaining the advantages of FFF beams [1–3]. The main advantage of FFF beams is the capability to deliver a higher dose rate in comparison to a standard beam that uses flattening filter (FF). High dose rate beam usage can reduce patient’s treatment time, thus reducing the risk of mistreatment caused by intrafraction motion and increasing patient comfort. Other dosimetric advantages of FFF beams are the reduction in head-leakage radiation and the reduction in out-of-field doses [1].

The application of FFF beams in advanced radiotherapy technique is often related to the usage of small field, for better conformity and better definition of the target volume. Small field dosimetry is a great challenge since the perturbation effects caused by the size of the detector’s active volume or detector’s materials could create a significant deviation [2,4]. The lack of lateral charged equilibrium also became a critical issue in small field dosimetry. Significant errors in beam output measurements can create uncertainties in beam data used by treatment planning systems that might lead to patient
mistratment [3]. This phenomenon encourages researchers to conduct a further study about detector response in small field.

There are several studies about detector response in small field. Wegener et al. [4] studied detector response by separating scatter and primary radiation for MV beams to understand the role of different phenomenon influencing the detector response in small fields. The authors proposed an idea to study detector response in FFF beams using a similar approach. In this study, scatter and primary radiation from 6 MV FFF beams were separated to study the detector response in each field for a better understanding of the contribution of every phenomenon influencing the detector response in small field.

2. Materials and Methods
The ionization chamber detectors CC13 (IBA Dosimetry GmbH, Germany), FC65G (IBA Dosimetry GmbH, Germany), and SNC600c (Sun Nuclear Corporation, USA) were used in this study. The main nominal characteristics of the detectors can be seen in Table 1. Measurements were carried out using Varian Trilogy linear accelerators (Varian Medical Systems, USA), capable to deliver both 6 MV FF and FFF photon beams. A Sun Nuclear 1D scanner phantom (Sun Nuclear Corporation, USA) was used for in-water measurements. The detector signal was recorded with Dose1 (IBA Dosimetry GmbH, Germany) electrometer with at least 5 readings per field size. Ionization chamber measurements were performed with detectors voltage of +300 V, -300 V, and +100 V to quantify polarity and ion recombination effects. Gafchromic EBT3 (Ashland, USA) was used for relative dose measurements and scanning process was done with Epson Perfection V700 (Epson, USA) scanner.

| Specifications          | Detectors       |
|------------------------|----------------|
|                        | CC13 | FC65G | SNC600c |
| Active volume          | 0.13 cm³ | 0.65 cm³ | 0.6 cm³ |
| Active length          | 5.8 mm  | 23.1 mm | 22.7 mm |
| Active volume radius   | 3.0 mm  | 3.1 mm  | 3.05 mm |
| Wall material          | C552  | Graphite | Graphite, paint |
| Wall thickness         | 0.070 g/cm² | 0.073 g/cm² | - |
| Center electrode material | C552  | Aluminum | Aluminum |

2.1. Detector response measurements
Detector response measurements were conducted with 6 MV FFF beams in three measurement configurations representing open field and approximations of both primary and scatter part of the beam as illustrated in Figure 1. Open field configuration (O) was open field measurements where detectors were positioned in the standard open field water phantom measurements, which was the superposition of the primary and scatter radiation. Scatter configuration (S) was done with detectors positioned under 10 mm diameter steel block placed in linac’s block tray, exposing the detectors only to scatter part of the radiation field. Detectors were positioned on the central beam axis in 10 cm depth from the surface and at 100 cm source-surface distance for open field and scatter configurations. Primary configuration (P) was done with detectors positioned inside mini phantom, approximating the detectors’ response to primary radiation with minimal scatter. Mini phantom was made from poly(methyl methacrylate) (PMMA) with 2.5 cm x 4 cm x 20 cm dimension used for primary beams configuration. The detector was placed vertically at 10 cm depth in the middle of the mini phantom. Measurement setup in this work was adapted from Wegener et al. [4] with some modifications. The detector response measurements were done in various field sizes ranging from 0.8 cm to 10 cm. The dose given in each measurement was 200 MU with 1120 MU/minute dose rate.

2.2. Film measurements.
Gafchromic EBT3 film was calibrated with the same setup as linac output calibration which was done with 6 MV FFF beam at 100 cm source-surface distance, 10 cm depth, and 10 cm x 10 cm field size in
3. Result and Discussion

3.1. Detector response measurements in the open field, primary, and scatter configurations.

Detector response in open field, primary, and scatter configurations are shown in Figure 2. The detector readings in terms of electric charge were corrected with polarity, ion recombination, and temperature – pressure correction factors. Figure 2(A) shows the detector readings in the open field configuration \((O)\). For field size less than \(4 \times 4 \text{ cm}^2\), detector reading decreases significantly due to volume averaging effects. The volume averaging phenomena affects FC65G and SNC600c more than in CC13 detectors caused by their difference in terms of active volume length and size, which FC65G has larger and longer active volume than SNC600c and CC13 respectively. For field size larger than \(4 \times 4 \text{ cm}^2\), detector reading slightly increases due to the increasing scatter radiation as the scatter medium getting larger as the field size increases. These results confirm that detector responses were heavily depended on its design (i.e. active volume) especially in small beams, similar to the previous studies \([3,5]\). There are some factors that could affect the detectors’ characteristics, such as the finite volume of the detector’s cavity, the atomic properties of the medium, the electron density of the cavity medium, and the extracameral components of the detector \([6]\). The density perturbation effects can be explained with Fano’s theorem, describing how the detector cavity’s density causing the dose compensation effect when the primary beam directed and not directed at the cavity. The atomic properties of the detector medium affect the interaction probabilities governing radiation transport inside a medium thus affecting the detector response. The extracameral components of the detector affect the detector response due to their difference in mass density or atomic properties with water. The interaction cross sections of extracameral components differ from water and over or under response of the detectors would happen since the number of electrons reaching the cavity is different than if the detectors were constituted of water.

The volume averaging effects in the detectors were also observed in the primary and scatter configuration as shown in Figure 2(B) and 2(C). In primary configuration \((P)\) measurement result shown in Figure 2(B), we could observe the constant detectors reading in field size larger than \(4 \times 4 \text{ cm}^2\). This result shows that scatter radiation was successfully kept at the minimum using the primary configuration with a mini phantom. In the scatter configuration \((S)\) measurement result as shown in Figure 2(C), we could observe the difference in each detector more clearly. The difference between FC65G and SNC600c was easier to observe rather than in open field and primary configuration.
FC65G and SNC600c detectors have a small active volume, radius, and length difference, but the influence of that small difference to detector reading could be more emphasized under scatter radiation configuration.

The comparison of open field (O), primary (P), scatter (S), and the sum of primary – scatter configurations measurement results for each detector are shown in Figure 3. The comparison of open field and the sum of primary – scatter configurations could show how close the primary and scatter configuration measurements approach to reproduce the open field measurements. The response in the open field could be reproduced from the scatter and primary beam set-up with a discrepancy ranging from 1.0% to 36%, as listed in Table 2 for each field and each detector. There are some factors that could contribute to the uncertainties which were detectors positioning, signal reproducibility, field size setting or jaws positioning reproducibility, and the measurement configuration reproducibility.

Table 2. Comparison in terms of percent differences between open field measurement results and the sum of primary – scatter configuration measurement results for each detector.

| Field Size | CC13  | FC65G | SNC600c |
|------------|-------|-------|---------|
| 0.8        | 31.0  | 3.4   | 5.7     |
| 1          | 19.5  | 21.3  | 3.7     |
| 1.6        | 5.3   | 36.0  | 1.0     |
| 2          | 9.8   | 30.3  | 4.0     |
| 2.4        | 12.5  | 27.2  | 5.2     |
| 3          | 14.1  | 27.5  | 6.1     |
| 3.2        | 14.3  | 26.3  | 5.3     |
| 4          | 13.4  | 28.0  | 6.7     |
| 6          | 14.4  | 26.4  | 6.5     |
| 8          | 14.0  | 25.5  | 6.3     |
| 10         | 13.7  | 24.5  | 6.3     |
3.2. Film measurement results

Calibration curve in terms of pixel value to absorbed dose for Gafchromic EBT3 film in 6 MV FFF photon beam was shown in Figure 4. The films were exposed with 5, 10, 30, 50, 100, 150, 200, 250, and 300 cGy photon beams. The calibration curve obtained was used to calculate the dose from the open field and scatter configurations measurements, as shown in Figure 5. The correlation between dose and pixel value was written in Equation (1), where \( y \) is absorbed dose in cGy and \( x \) is the pixel value. The coefficient of determination \( (R^2) \) for the calibration curve is 0.990.

\[
y = 0.0000008x^2 - 0.0649x + 1321.4
\]  

(1)

In the open field configuration, shown in Figure 5(A), the dose readings obtained from EBT3 film increases as the field size was getting larger. For field size ranging from 4 x 4 cm\(^2\) to 10 x 10 cm\(^2\), the dose readings tend to stay constant which differed from ionization chamber measurement results trend. This phenomenon could be caused by film measurement uncertainties that could happen because of fading in film before scanning caused by environment condition or scanning process uncertainties [7]. The measurement results of scatter configurations, shown in Figure 5(B), shows that dose gradually increases as the field size getting larger. This result shows a similar trend with the ionization chamber measurement, in which the dose recorded increases with field size due to increasing scatter medium.

Figure 4. Gafchromic EBT3 calibration curve for 6 MV FFF photon beams.
4. Conclusions
Observing the scatter and primary radiation separately allow us to study phenomenon influencing the detectors’ response such as volume averaging more clearly. The results of this study show a similar trend compared to the previous study. For further studies, observing the detector response under scatter radiation can be beneficial in semiconductor or different types of detectors to study over response or under response of different detector materials and to study the detector energy dependence characteristics. The evaluation and comparison between FFF and WFF (with flattening filter) beams will also be considered in a further study.

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