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Technical note: A new wedge-shaped ionization chamber component module for BEAMnrc to model the integral quality monitoring system®

Oluwaseyi Michael Oderinde, FCP du Plessis*

Department of Medical Physics, University of the Free State, PO Box 339, Bloemfontein 9300, South Africa

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ABSTRACT

The purpose of this study was to develop a new component module (CM) namely IQM to accurately model the integral quality monitoring (IQM) system® to be used in the BEAMnrc Monte Carlo (MC) code. The IQM is essentially a double wedge ionization chamber with the central electrode plate bisecting the wedge. The IQM CM allows the user to characterize the double wedge of this ionization chamber and BEAMnrc can then accurately calculate the dose in this CM including its enclosed air regions. This has been verified against measured data.

The newly created CM was added into the standard BEAMnrc CMs, and it will be made available through the NRCC website. The BEAMnrc graphical user interface (GUI) and particle ray-tracing techniques were used to validate the IQM geometry. In subsequent MC simulations, the dose scored in the IQM was verified against measured data over a range of square fields ranging from 1×1–$30 \times 30\ cm^2$.

The IQM system is designed for the present day need for a device that could verify beam output in real-time during treatment. This CM is authentic, and it can serve as a basis for researchers that have an interest in real-time beam delivery checking using wedge-shaped ionization chamber based instruments like the IQM.

1. Introduction

Advanced radiotherapy (RT) treatment techniques such as intensity modulated radiotherapy (IMRT) and volumetric modulated arc therapy (VMAT) have optimized radiation treatment and as well minimize the absorb dose received by critical organs at risk (OAR) (Mayles et al., 2007; Bucci et al., 2005; Roopashri and Baig, 2013; Ahmad et al., 2012; Nakamura et al., 2014). The quality assurance (QA) of these treatment techniques is quite complicated and time-consuming (Ishikura, 2008; Connell and Hellman, 2009; Thariat et al., 2013). A continuous effort has been made on image guidance radiotherapy (IGRT) to monitor the modern linear accelerator (linac) (Williamson et al., 2008). IGRT allows for online replanning of the dose and geometry. With this progress, there is still a dosimetric uncertainty in a modified treatment plan of IMRT and VMAT. Therefore, there is a huge interest in verifying and validating the treatment beams during real-time treatment. Few monitoring devices have been utilized in recent time for offline verification, but little has been achieved in online verification (Islam et al., 2009).

The Integral quality monitoring (IQM) system (iRT Systems, Germany) is an independent real-time treatment verifying instrument that measures the beam output and compares it with expected values within a typically 2% dose margin. The aim is to validate the integrity and accuracy of the delivered beams on the treatment plan data calculated for the patient. This device has a large double wedge-shaped ionization chamber that is attached to the linac head in real-time radiotherapy (Islam et al., 2009; Chang et al., 2013; iRT Systems, 2014). The gradient of the wedge-shaped ionization chamber aligns with the MLC leaf movement.

Monte Carlo (MC) codes have been utilized in several studies as dose calculation engines for clinical radiotherapy. It accurately calculates the dose distribution in heterogeneous phantoms were physical measurement seems difficult (Chetty et al., 2007; Paganetti et al., 2004; Mesbahi, 2006; Michaeloderinde and Obed, 2015).

The BEAMnrc MC user code was designed to accurately simulate electron/photon transport through all relevant components of a radiotherapy machine (Rogers et al., 2011, 1995; Chetty et al., 2007). To model a machine such as a linac radiation head, several component modules (CMs) would be arranged upstream. Hitherto, none of the existing CMs could model the IQM system that is essentially a double-wedge ionization chamber (Rogers et al., 2011). In this study, a new CM (IQM) was designed and added to the existing CMs for the BEAMnrc user code. The new CM was designed to simulate a wedge-shaped ionization chamber that would calculate the dose distribution in its two enclosed air regions. The geometry of the IQM CM was validated by utilizing the ray-tracing technique. The ray-tracing method is used to test the geometry of a CM (Heath and Seuntjens, 2003). Macros

* Corresponding author.
E-mail address: DuPlessisFCP@ufs.ac.za (F. du Plessis).

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(nrcaux.mortran) in the BEAMnrc code allow an output detail of particle interactions when crossing boundaries of the CM. It outputs the geometry of all the CMs in a simulation to the.egsgeom file that is displayed by using EGS_Windows or a graph plot. This file is available when IWATCH is set to four (4). IWATCH set to four, and the last interaction (ZLAST) simulation parameters cannot function simultaneously. If the user wants to score the last interaction into the phase space file, IWATCH parameter should be changed from four. (Rogers et al., 2011).

To test the CM in practice, an accurate MC model of an Elekta Synergy that produces 10 MV photon beams was used in BEAMnrc simulations with the IQM CM fixed below the treatment head facing the photon beams. MC dose data and real measurement data were compared for several field sizes.

2. Materials and methods

2.1. Integral quality monitoring system®

The IQM device (iRT Systems GmbH Koblenz Germany) consists of a wedge-shaped ionization chamber that has a sensitive volume of 550 cm^3, it is capable of monitoring a 40 × 40 cm^2 field defined at isocenter. The shape of the IQM was defined by the outer two electrode plates (polarizing electrodes) and the inner electrode plate designated as the collector. Each of the electrodes is 2 mm thick and is made of aluminum (Fig. 1). The gradient of the outer electrodes was designed to produce a change in response of approximately 0.5% mm^{-1} near the center of the air chamber and maintained at 500 V during normal operation. The whole chamber has a thickness of 4 cm with a sensitive area of 26 × 26 cm^2 that is fixed to the shielding tray (Elekta) or the wedge tray (Varian) of the linac. The IQM has an integrating electrometer, an inclinometer for volumetric modulated arc therapy (VMAT), thermometer, barometer, battery and Bluetooth interface for signal transfer to the IQM manager (iRT Systems, 2014).

2.2. IQM component module

The IQM CM (Fig. 2) was designed to model the wedge-shaped ionization chamber. The geometry of the ionization chamber model requires three layers to define the electrode plates. The square brackets [1, 2], and [3] as shown in Fig. 2 denote the defined layer. Above each layer is ZMIN and below each layer is ZMAX, while ZTHICK is the difference between ZMAX and ZMIN for each layer. ZTHICK defines the boundary between each layer along the z-axis. As conventional, RMAX defines the maximum boundary of the CM in the XY-plane. Three regions were created in each layer for effective dose calculation as seen in Fig. 2. Shown are the front air region (FR) which is the region in front of the electrode plates in the model, the central and outer region (CR and OR), and back air region (BR) which is the region at the back of the electrode plates. CR and OR are defined as one region which consists of the electrode plates and the thick edge of the wedge chamber. Layer two has no FR and BR in order to have a flat plane design. Regions were created in IQM_cm.mortran and in IQM_macro.mortran; coding HOWFAR, HOWNEAR, DNEAR, WHERE AM I, the mass dose zone and all other subroutines to define the IQM geometry and dose scoring regions. Like other CMs on the BEAMnrc GUI, the IQM CM requires input from the user for accurate geometry definition. The manufacturer's specification was used to model the IQM in BEAMnrc.

2.3. Monte Carlo simulation of the 10 MV photon beam for benchmark measurements

To correctly simulate the dose scored in the air chamber of the wedge-shaped ionization chamber, the 10 MV photon beam of the simulated linac must be closely matched against measured parameters such as the percentage depth dose, profiles, and relative output factors. This is to be sure that there are no discrepancies in the photon beam between simulation and measurement. The Elekta Synergy linear accelerator (linac) head was modeled according to the manufacturer's specification. For dosimetry, the Agility 160-leaf MLC of the Elekta Synergy linac operating at 10 MV was simulated. The linac was modeled using the BEAMnrc software package, and the dose was calculated using the DOSXYZnrc software package. The source model of the MC simulation was verified for accuracy by comparing depth dose curves and lateral beam profiles of 5 × 5, 10 × 10, 20 × 20 and 30 × 30 cm^2 fields with physical measurement using a Gamma analysis criterion of 2%/2 mm (Xing et al., 2015; Low, 2010; Huang et al., 2014; Kim et al., 2014). Relative output factors for 1 × 1–30 × 30 cm^2 fields were validated by physical measurement using the local percentage difference as recommended in articles (Jabbari et al., 2013; Tayalati et al., 2013; Mesbahi et al., 2007; Oliveira et al., 2013; Juste et al., 2007).

The number of histories was carefully defined to achieve an uncertainty that is less than 1% in the useful beam area. A predetermined low energy limit was carefully set for global electron cut-off energy (ECUT) (set to 0.7 MeV) and global photon cut-off energy (PCUT) (set to 0.01 MeV) that was utilized for the simulation of electrons and/or photons transport in BEAMnrc and DOSXYZnrc. This was set in order not to bias the high energy transport and to reduce the effect of low dominant energy transport during tracking (Chetty et al., 2007). The parallel circular electron beams were incident on the center of the front of the first CM (target of the linac head) for all the simulations in this study.

2.4. Geometry validation

Validation of the CM geometry was done by ray-tracing of the particle tracks through the IQM CM. This method allows graphical display of the simulation coordinates of the IQM CM as explained in Section 1 above. The ray-tracing method tests the correctness of the IQM's geometry in BEAMnrc. The IQM's coordinates were available in the IQM_egsgeom file after running the simulation.

2.5. Measured IQM signal response and the correlation of Monte Carlo simulation dose

The IQM electronic signal is directly proportional to dose scored in the air region of the wedge-shaped ionization chamber which in turn, is proportional to a number of monitor units MUs set. The electronic signal is a measure of the radiation output of the linac transmitted through the dual wedge-shaped ionization chamber of the IQM device. The dosimetry system measures the amount of radiation and then transfers the readings to the IQM applications for verification using the

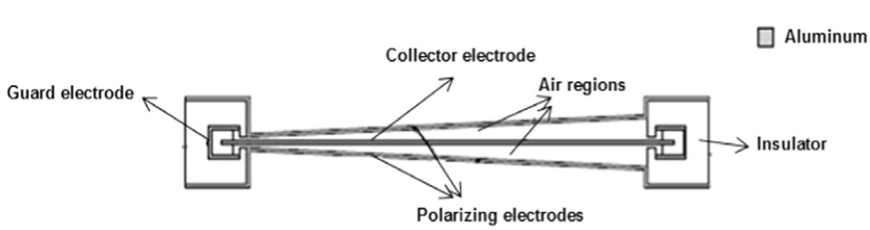

Fig. 1. Illustration of the IQM system. It is fixed onto the linac head to measure the beam output during patient treatment. (iRT Systems, 2014).

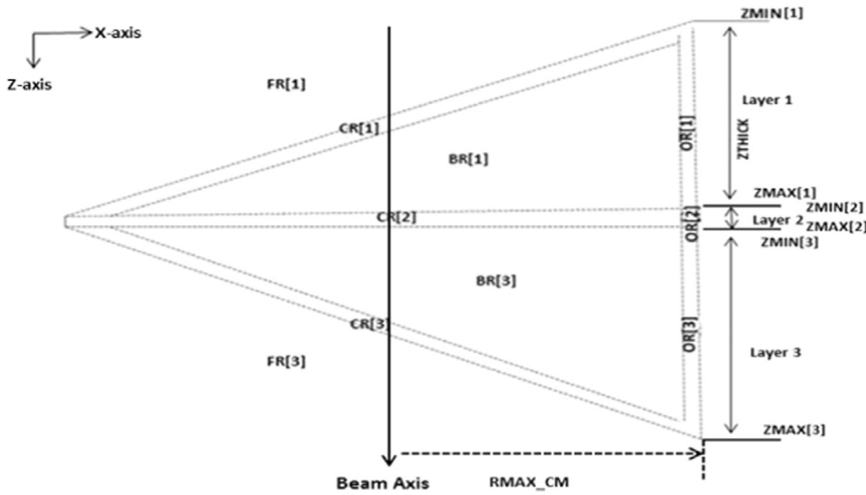

Fig. 2. The IQM CM model is showing the three regions and layers of its main construction.

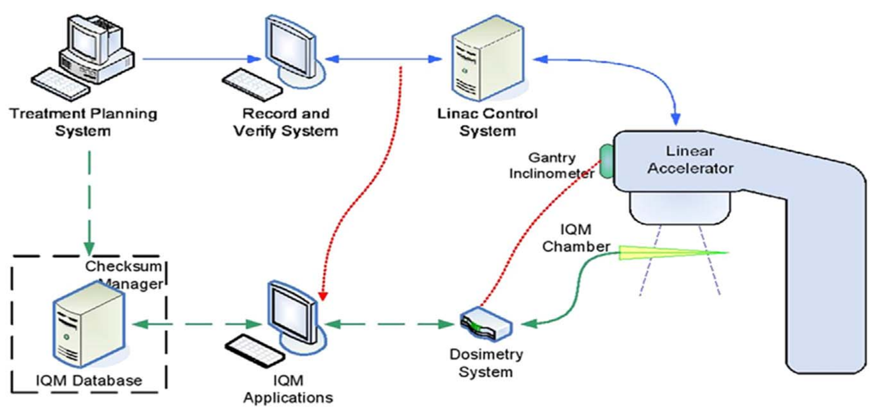

Fig. 3. Clinical workflow of the IQM system [permission granted] (iRT Systems, 2014).

reference reading in the IQM database. The clinical workflow is depicted in Fig. 3. For Monte Carlo simulation, the actual dose per simulated history is scored in the air region of the chamber.

In order to relate the measured IQM electronic signal and the MC dose in the chamber, the IQM signal was divided by the product of relative output factor (ROF) and monitor unit (MU) of the MC dose. This is shown in steps below. The spatial response of the wedge-shaped chamber (electronic signal S_{IQM}) is predicted as (iRT Systems, 2014; Islam et al., 2009):

$$S_{IQM} = MU.\ AOF(x,y) \oint_{Area} I_{field}.\ S(x,y) \tag{1}$$

From Eq. (1), MU is the monitor unit, $AOF(x,y)$ is the area integrated output factor for the collimator setting which is a function of square or equivalent square fields (An increase in square field size causes an increase in machine output (Liu et al., 1997)), I_{field} is the fluence distribution, and $S(x,y)$ is the spatial chamber response function. The IQM electronic signal corresponds to the spatial sensitive dose-area product for each beam segment (Islam et al., 2009; iRT Systems, 2014). If the electronic signal is divided by the ROF for the segment size and the MU of the MC dose, then we can relate $\oint_{Area} I_{field}.\ S(x,y)$ to MC dose-area product (calculated signal).

The following steps were followed to calculate the MU and ROF for the MC dose:

Step 1: MC relative dose distribution $R(x,y,z)$ was calculated by normalizing the spatial integral dose scored for each simulated field $D_i(x,y,z)$ in the wedge-shaped chamber to the MC reference dose $D^{ref}_{cax,\max}$ for 10 MV photon beams (Ma et al., 2004). The MC reference dose in this study was defined as the depth of maximum dose scored in a water phantom along the central axis for the $10 \times 10\ \text{cm}^2$ field at 100 cm source-to-surface distance (SSD) for 10 MV photon beams as used clinically (Rosenberg, 2008; Khan, 2011).

$$R(x,y,z) = \frac{D_i(x,y,z)}{D^{ref}_{cax,\max}} \tag{2}$$

Step 2: The MC relative output factor (ROF) in Eq. (3) is the ratio of the depth of maximum dose $D_{i,cax,\max}$ scored in water phantom along the central axis for a simulated field to the MC reference dose $D^{ref}_{cax,\max}$.

$$ROF = \frac{D_{i,cax,\max}}{D^{ref}_{cax,\max}} \tag{3}$$

Step 3: The MU for any spatial simulated field *(x,y,z)* transmitted through the wedge-shaped ionization chamber using MC is:

$$MU = \frac{D_p(x,y,z)}{R(x,y,z).\ ROF} \tag{4}$$

where $D_p(x,y,z)$ is the prescribed dose, $R(x,y,z)$ is the relative dose distribution, and ROF is the MC relative output factor as stated in Eqs. (2) and (3) respectively (Ma et al., 2004). For example; if the prescribed dose is 100 cGy for an MC relative dose distribution of 0.8 and relative output factor of 1.1, then the amount of MU needed to be delivered to this dose will be 113.64 based on Eq. (4).

Step 4: To relate the MC simulated dose in the wedge-shaped ionization chamber with the physical measured electronic signal in the IQM system, the measured electronic signal S_{mes} is divided by the product of MU calculated in Eq. (4) and ROF calculated in Eq. (3).

$$S_{cal} = \frac{S_{mes}}{MU.\ ROF} \tag{5}$$

where S_{cal} is now the new value of the measured signal (an electronic signal) that will be correlated with the MC signal (MC simulated dose).

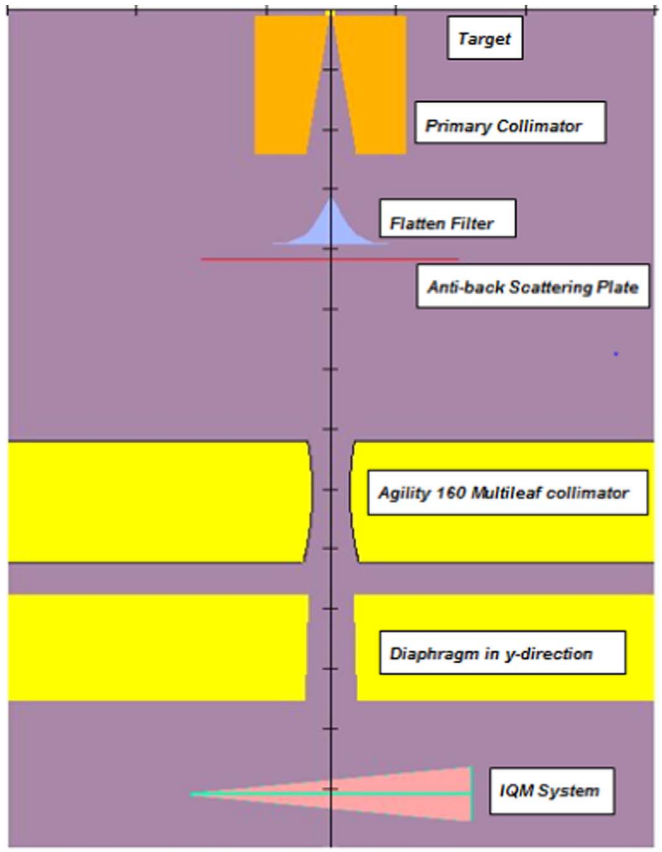

Fig. 4. Linac head model with the IQM CM attached to it shown in the BEAMnrc GUI. The IQM shape is drawn based on the input parameters in Table 1.

Eq. (5) can be restated using Eqs. (3) and (4) as:

$$S_{cal} = \frac{S_{mes}.\, R(x, y, z)}{D_p(x, y, z)} \tag{6}$$

The calculated electronic signals S_{cal} and the MC calculated dose were normalized to their respective $10 \times 10\ \text{cm}^2$ field.

3. Results and discussion

3.1. IQM component module design

A linac head model with the new IQM CM attached is depicted in Fig. 4. This is a necessary addition to BEAMnrc for studying wedge-shaped ionization chambers such as the IQM. The IQM control tool in the BEAMnrc GUI allows the user to define the geometry parameters of the IQM model. To obtain the graphical display of the IQM in Fig. 4, input parameters were defined in Table 1.

The dose regions, energy cut-off, and region materials were defined for the central and outer region, the front region, and back region for each layer. The dose scoring region value is used to differentiate one region from another and materials for each medium in every layer. The user defined materials are aluminum, vacuum, and air for the IQM model in Fig. 4. These materials could be changed to any other materials as specified by the user and seventeen (17) more layers could be added on metal layers to suit the user. The input parameters are flexible and user-friendly which could be adjusted to suit the user's purpose.

The flexibility of the IQM CM was to model a wedge-shaped ionization chamber and to create regions for dose deposition. It gives room for the user to define the dose region number, component materials, dimensions, and spatial specifications. Incorporation of the IQM CM into the BEAMnrc GUI modifies the landmarks set in the BEAMnrc GUI that was downloaded from the National Research Council Canada

Table 1
IQM input parameters.

Reference parameters	Variable parameters
Half-width of outer square boundary (RMAX_CM)	13 cm
Number of layers	3
Distance from front to reference plane (ZMIN[1])	55.5 cm
Distance to back to reference plane (ZMAX[1])	57.4 cm
Positive x dimension of opening at front (XFP[1])	12.8 cm
Positive x dimension of opening at back (XBP[1]]	−12.6 cm
Negative x dimension of opening at front (XFN[1])	12.6 cm
Negative x dimension of opening at back (XBN[1])	12.8 cm
Outer x edge (XMAX[1])	12.9 cm
Distance from front to reference plane (ZMIN[2])	57.4 cm
Distance to back to reference plane (ZMAX[2])	57.6 cm
Positive x dimension of opening at front (XFP[2])	12.8 cm
Positive x dimension of opening at back (XBP[2]]	12.8 cm
Negative x dimension of opening at front (XFN[2])	−12.8 cm
Negative x dimension of opening at back (XBN[2])	−12.8 cm
Outer x edge (XMAX[2])	12.9 cm
Distance from front to reference plane (ZMIN[3])	57.6 cm
Distance to back to reference plane (ZMAX[3])	59.5 cm
Positive x dimension of opening at front (XFP[3])	−12.6 cm
Positive x dimension of opening at back (XBP[3]]	12.8 cm
Negative x dimension of opening at front (XFN[3])	−12.8 cm
Negative x dimension of opening at back (XBN[3])	12.6 cm
Outer x edge (XMAX[3])	12.9 cm

(NRCC) website. This modification must be done on the BEAMnrc codes when there is an intention to add a new CM; else access to the new CM on the interface will not be possible. Successful compilation of the IQM CM and the code run authenticates the sub-routine macros of EGSnrc code in the BEAMnrc code. The IQM CM will be made available to interested parties through the NRCC website.

3.2. Validation of the IQM geometry by ray tracing

Fig. 5 shows a two-dimensional ray tracing graph of the IQM CM coordinates. It specifies the boundaries of the IQM model in the simulation. The arrows in Fig. 5 were used to trace out the actual image of IQM model on the specified boundaries.

Graphical image and ray tracing technique verifies the IQM CM geometry. "Ray tracing method" as a term was not directly mentioned in BEAMnrc user manual ((Rogers et al., 2011) but the nrcaux.mortran routine performs the same function as ray tracing which is to use particle step/interaction or particle tracking to output detailed boundaries of the simulation CMs in egsgeom. Ray tracing increases the simulation time due to boundary crossing, and some articles have suggested MC simulation techniques for ray tracing calculation (Jacques et al., 2011; Jabbari, 2008).

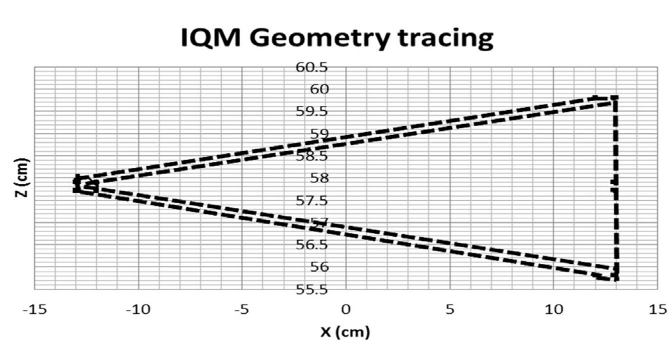

Fig. 5. 2D (z and x- axis) projection of a ray tracing of the IQM CM. The z-axis represents the thickness of the IQM model parallel to photon incident beam while x-axis represents the lateral distance of the IQM model across the incident beam.

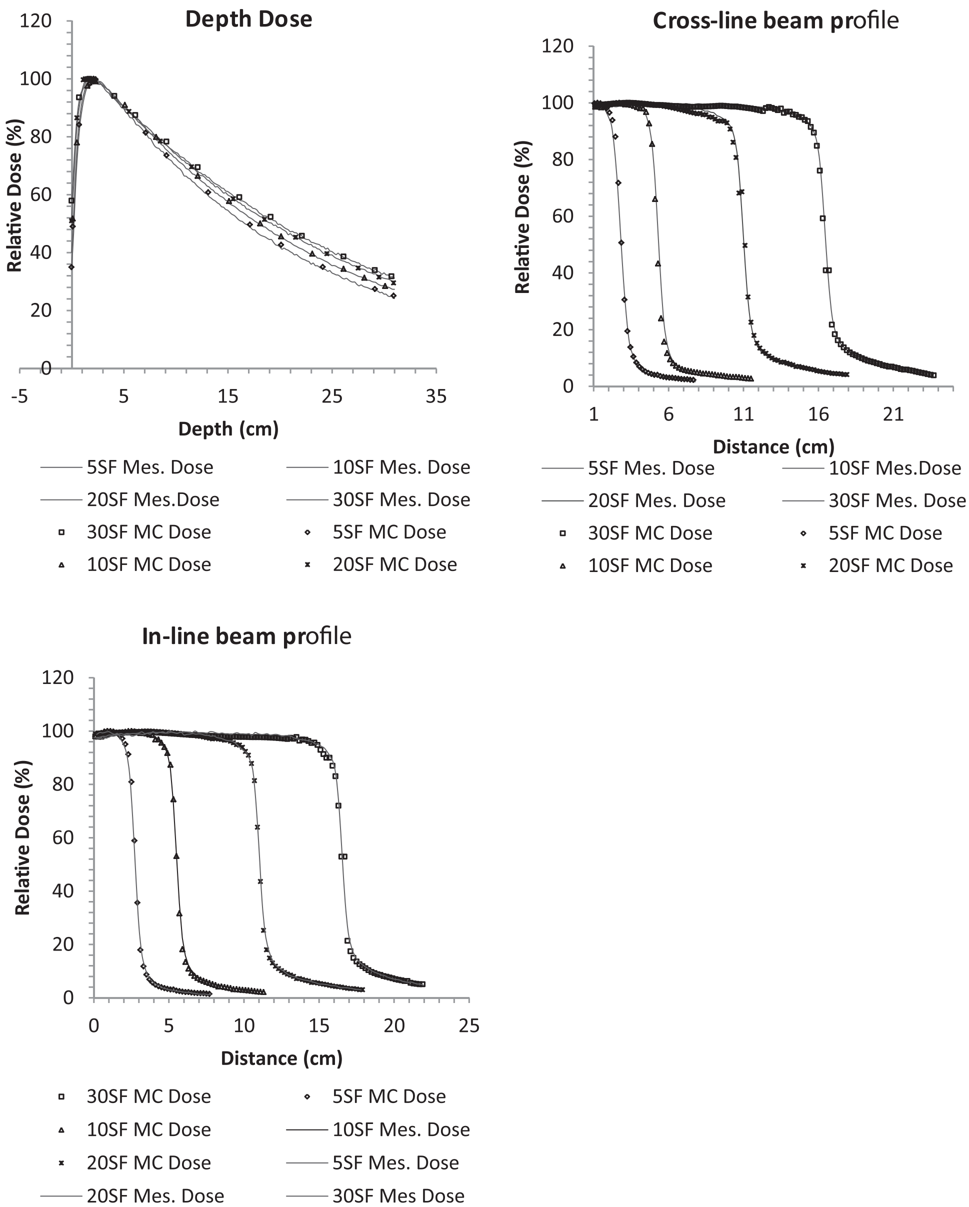

Fig. 6. Comparison between measurement and MC depth dose, cross-line profile and in-line profile data for 5 × 5 cm^2 to 30 × 30 cm^2 fields obtained at 100 cm SSD for a 10 MV photon beam.

3.3. Accurate source model

As stated previously, the IQM CM was used in MC simulation to evaluate its scored dose against measured signal data. Therefore an accurate source model is needed. Fig. 6 shows the comparison between measured and MC depth dose curves and lateral beam profile curves at 10 cm depth for 5 × 5, 10 × 10, 20 × 20 and 30 × 30 cm^2 fields obtained at 100 cm SSD for 10 MV photon beams. Table 2 shows the comparison between measured and MC relative output factors for 1 × 1–30 × 30 cm^2 field sizes at 90 cm SSD for 10 MV photon beams. This is the data for a full simulation of an Elekta Synergy linac.

The MC simulation benchmarked against measurement agreed to 2%/2 mm for the depth dose curves and the lateral beam profiles. The majority of the MC simulated data and the measured data for the relative output factor agreed to within 1.5% of the local dose.

A number of histories taken to achieve the statistical uncertainty that is within 1% in this study were above 15 billion for the largest field (30 × 30 cm^2).

Table 2
Relative output factor (ROF) at 90 cm SSD for 10 MV photon beams.

Square field size (cm^2)	Simulated ROF	Measured ROF	Local diff (%)
1 × 1	0.6792	0.6714	1.1648
2 × 2	0.8224	0.8115	1.3543
3 × 3	0.8771	0.8647	1.4422
4 × 4	0.9200	0.8964	2.6318
5 × 5	0.9244	0.9205	0.4172
10 × 10	1.0000	1.0000	–
15 × 15	1.0559	1.0460	0.9436
20 × 20	1.0608	1.0759	1.4082
25 × 25	1.0842	1.0960	1.0770
30 × 30	1.1194	1.1100	0.8455

3.4. IQM signal response

Fig. 7 showed the normalized IQM response for 1 × 1–30 × 30 cm^2 fields for 10 MV photon beams measured (calculated electronic signal S_{cal} which was expressed in Eqs. (5) and (6) above) and simulated (calculated dose).

In Fig. 7, the calculated electronic signal and the simulated dose

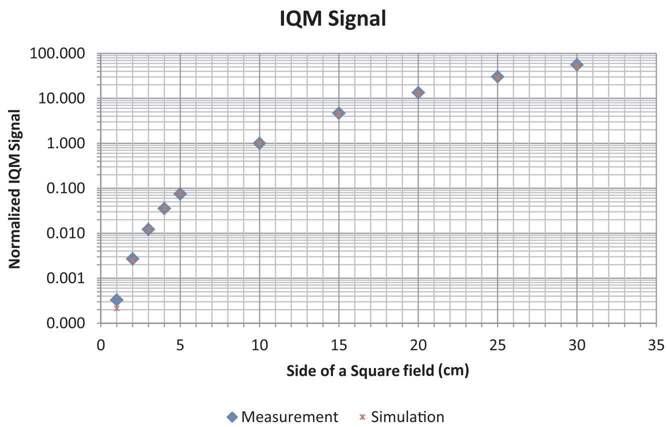

Fig. 7. IQM signal response plotted on a semi-log scale for 1 × 1–30 × 30 cm^2 fields for 10 MV photon beams.

increase with an increase in square field size with the data closely in agreement over the range of field sizes. The calculated electronic signal in the double wedge-shaped ion chamber will produce a signal of the order of nC (nano coulomb) while the MC simulation data or the calculated dose has a unit of cGy cm^2 (dose-area product). Normalization allows rescaling of both outputs. Validation of the linac model used in this study gives the confidence that there are no significant discrepancies in the real and simulated photon beams upstream of the IQM model. The simulated response is possible since the MC and real photon beam have the same ROFs, PDDs and profiles over the fields studied. The electronic signal generated by the IQM and the dose scored in the wedge-shaped ionization chamber model increased with an increase in square field sizes due to an increased charge collection and energy deposition in the air region between the inclined plates.

The ability to use MC simulation to calculate dose in the ionization chamber is one of the advantages of EGSnrc code. The EGSnrc code has the ability to model ionization chambers accurately because the exact boundary crossing algorithms used allows correct calculation of dose in each side of a boundary as charged particle approaches and also allows electron transport refinements (Kawrakow et al., 2013).

The signal of the prototype IQM system is not based on spatial dose calculation but rather on the electronic signals generated by the radiation beam. Since the IQM system is still in its development stage, the end point of its functionality is to calculate spatial dose as stated by the guiding articles (Paliwal et al., 1996; Chang et al., 2013; Islam et al., 2009). Theoretically, the output of an ionization chamber detector should be related to the absorbed dose in the chamber.

4. Conclusion

This study described the development of a new IQM component module which can serve as a basis for researchers that have an interest in MC study of wedge-shaped ionization chamber systems. Application of MC techniques to an online dose monitoring is authentic. It demonstrates that MC radiation transport method is virtually unlimited when it comes to solving radiation transport and dose calculation challenges.

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