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Monte Carlo study on a new concept of a scanning photon beam system for IMRT

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Abstract. Intensity-modulated radiation therapy (IMRT) is almost exclusively realized using a multi-leaf collimator (MLC). In this work we investigated alternative approaches to realize an IMRT – scanning photon beam system. The technical realization of this concept required investigating the influence of various design parameters on the final small photon beam. This was done using Monte Carlo (MC) simulation methods. The resulting photon beam that is to be scanned should have a diameter well less than 10 mm at a source-surface distance (SSD), and the penumbra should be as small as possible. A first draft for this system, based on the PRIMUS 6 MV accelerator at DKFZ (Deutsches Krebsforshungszentrum), was proposed and modeled using the BEAMnrc/EGSnrc MC code. We then proposed and studied a new geometry of the source-target-collimator system. Calculations were done for 10^8 particles, using an electron energy cut-off (ECUT) = 0.7 MeV, and a photon energy cut-off (PCUT) = 0.01 MeV. The influence of different collimator parameters, different target construction and various incident electron beam characteristics was studied. Calculations of the dose absorbed in the water were performed for 8 different collimators at a distance of 40 cm from the collimator exit, which is the medical requirement. Results of the dose distribution calculations are presented as photon beam profiles with the values of full width at half-maximum (FWHM) and penumbra (PM) for every beam profile. The influence of target construction was studied for different thicknesses of target and material minimizing electron contamination. The influence of the following characteristics of the incident electron beam was also investigated: size of electron beam, energy, displacement of the beam from the axis of target-collimator system, shape of the electron beam profile. The field dose distribution of the photon beam was calculated for the collimators giving the beam profiles. Basing on the work performed in this investigation, it will be possible to define adequate parameters for the target-collimator system as well as on the scanning electron beam for new IMRT system.

Key words: Monte Carlo (MC) simulations • medical accelerators • intensity-modulated radiation therapy (IMRT)

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Introduction

IMRT is a well-established technique in radiotherapy. This technique has important potential to further reduce the absorbed dose to organs at risk (and thus the risk of normal tissue complications), while also delivering a conformal dose to irregularly shaped target volumes. It is expected that this technique of radiotherapy will play a dominant role in the years to come.

Currently, IMRT is almost exclusively realized using a MLC. Other methods use compensators, but these are very time-consuming procedures. Several MLC applications are well known (e.g. static "step and shot" IMRT, or dynamic "sliding window" IMRT). However, there are some items of concern regarding their application:

a) The concept of IMRT is totally independent of the concept of an MLC, hence it is not certain that the use of MLCs is the best solution for IMRT.
b) Although well suited, MLCs were not originally designed for IMRT.

c) With MLCs, the ratio of the part of the beam that is used for treatment compared to total beam shape may seem problematic. This occurs because a medical linac is designed to provide large fields, while IMRT requires a large number of small field sections.
d) For IMRT, both large fields and a high resolution (dependent on leaf width) are desirable. However, improving MLC-based IMRT solutions by using large MLCs with a fine resolution, raises more and more complex problems of a mechanical nature in the control system of the MLC.

Therefore, it appears useful to investigate alternative approaches to realize intensity-modulated fields, i.e. methods that are not based on an MLC.

An alternative approach can be based on a scanning collimator system. It has been shown that it is technically feasible to construct a scanning collimator with a small aperture in such a way that the collimator is moving across the 2-dimensional (2-D) surface of a sphere with the beam source in the centre of this sphere [2]. In order to provide a large scanning area, it would appear that a large photon field must be provided at the collimator entry side. However, it is difficult to "carve out" a very small beam diameter from a large entry field area.

If it is feasible to force an electron beam in arbitrary directions using a 2-D system of bending magnets, however, the electron beam and the collimator could then be combined in a radiation unit in such a way that the scanning electron beam is always forced to hit to a Bremsstrahlung target that is directly placed at the entrance side of the scanning collimator. Thus, a scanning photon beam system can be established (Fig. 1).

The shape of the photon beam will predominantly depend on the collimator characteristics. In order to provide a photon beam that is appropriate for a variety of intensity modulated fields (very large fields, very small fields, high intensity gradients, small intensity gradients), a variable collimator aperture should provide a set of different beam profiles. It is suggested to construct a collimator with a fixed set of quadratic apertures.

It is a prerequisite for such a radiation unit that the centre of the electron beam is exactly correlated with the central axis of the collimator. To meet this requirement, a special control system must be developed to correctly steer the electron beam. In addition, it should be possible to modulate the intensity of the photon beam by a controlled change of the intensity of the electron beam from pulse to pulse.

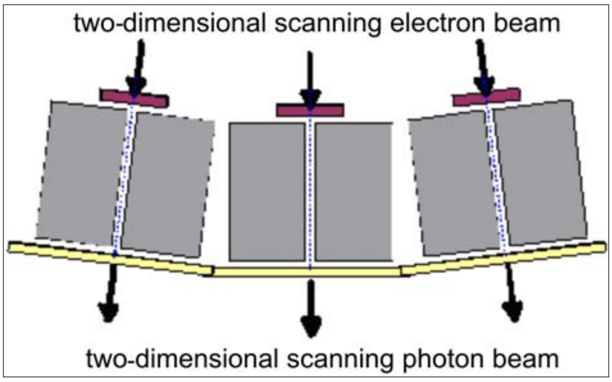

Fig. 1. Scanning movement of electron and the narrow photon beam.

The aim of this paper is to investigate the technical requirements to implement this concept. In particular, we studied the influence of design parameters of the target-collimator-monitor system on the quality of the desired intensity modulation.

Methods

MC methods to simulate the complete gantry system of conventional linacs are well established. The scanning photon beam system for IMRT was proposed and modeled with the BEAMnrc/EGSnrc code [1]. The input parameters for the complete existing target-collimator system (PRIMUS 6 MV accelerator) were used to study the basic influence of the single components on the beam characteristic, i.e. on the photon fluence differential in energy and direction.

Definition of requirements on the resulting photon beam

a) The photon beam to be scanned should have a diameter well less than 10 mm at SSD.
b) The penumbra should be as small as possible.

First draft for a target-collimator system

A first draft for a target-collimator-ionization chamber system was proposed and modeled with the MC code. This system is simply a copy of the system used for the PRIMUS accelerator (Fig. 2).

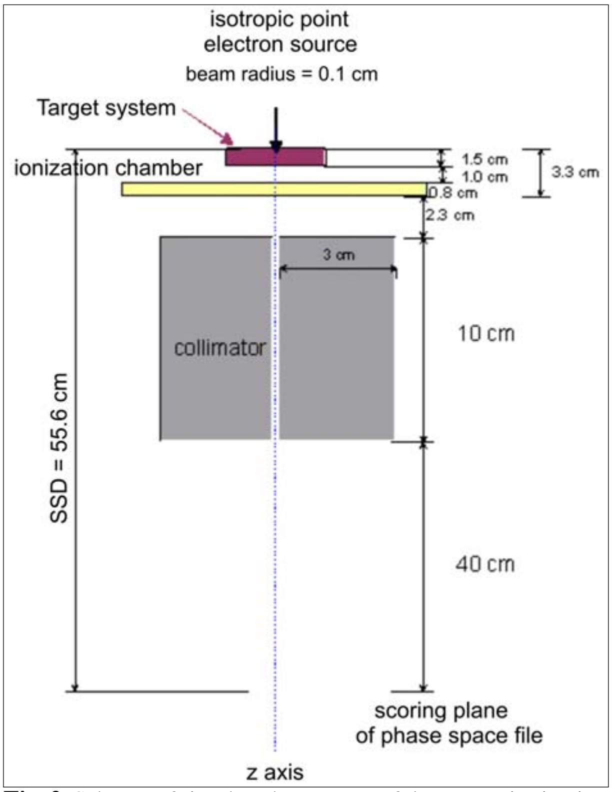

Fig. 2. Scheme of simulated geometry of the target, ionization chamber and collimator.

Table 1. FWHM and PM of beam profile calculated for different collimators

Number of collimator	Entrance aperture r (mm)	Exit aperture R (mm)	FWHM (mm)	PM (mm)
#1	1.0	2.8	20.92	3.20
#2	2.8	2.8	17.64	6.47
#3	1.0	1.0	6.56	3.14
#4	2.0	1.0	7.70	3.17
#5	3.0	1.0	8.56	3.40
#6	2.0	0.5	5.46	2.69
#7	1.0	0.5	5.18	2.24
#8	0.5	0.5	5.52	2.30

The source of electrons used in the calculation was a "point source" at a distance of 2.86 cm from the target, the radius of the electron beam on the target r_e was 1 mm, the energy spectrum of electrons ranged from 6.174 MeV up to 7.103 MeV (as in the PRIMUS accelerator).

Calculations were done for 10^8 incident electrons, using ECUT = 0.7 MeV, and PCUT = 0.01 MeV. Calculation time for each collimator was 14 h. For each collimator aperture, the energy fluence was calculated in 20 rings, each of 1 mm thickness, ranging from the beam axis to 2 cm off-axis on the surface at a distance of 40 cm from the collimator exit. The distance of 40 cm was based on reasonable medical requirements (see Fig. 1).

The terms r and R signify, respectively, the radius at the entrance and exit aperture of the collimator. Several combinations of r and R were investigated (see Table 1).

The influence of different parameters was investigated for 8 different collimators. All MC calculations provided data as energy fluence/incident electron/energy bin in units of cm^{-2} at a distance of 40 cm from the source. Calculations of the dose (D) absorbed in water have been performed by:

$$D = \sum_i \Phi_i \cdot E_i \cdot \frac{\eta_{en}}{\rho}(E_i) \cdot \Delta E_i \quad (1)$$

for energy steps i = 1, 2, 3, …, 20 (meaning that 20 equally spaced energy bins were provided). Φ_i signifies the energy fluence per ring divided by the number of incident electrons (10^8) used as input for the simulation. η_{en}/ρ signifies a mass energy-absorption coefficient for water. ΔE is equal to 0.38 MeV for all i-s. D, the absorbed dose in water for the area of each ring, is expressed in units of MeV/g (1 MeV/g = 1.6×10^{-10} Gy). Parameters of collimators are given in Table 1.

Influence of target construction

Other calculations were performed to estimate the influence of different target construction on photon beam dose distribution. This was done because the original PRIMUS target system was designed with a 1 cm thick layer of carbon to minimize electron contamination. For the scanning photon beam system, however, any material that would contribute to a scattering of the photons should be avoided in order to get a beam as narrow as possible. For this investigation, the energy fluence distribution was calculated already at a distance of 3.3 cm from the top of the target, i.e. before the collimator (see Fig. 2). Calculations were made for 10^7 particles.

Influence of the incident electron beam characteristics

Calculations referring to the influence of electron beam characteristics on the dose distribution in the photon beam were also done. These calculations refer to the influence of a) the size of electron beam on the dose distribution of photon beam, b) the energy and c) the displacement of electron beam from the axis of system.

New geometry

A "new geometry" of the simulated system of target, collimator, and chamber, was introduced in further simulations (Fig. 3). (1) A new distance between target and collimator was introduced, and (2) the ionization chamber was moved behind the collimator.

1. The collimator is at a distance of 0.5 cm from the target. This ensures that more photons from the target will enter the collimator than from a distance of 5.6 cm.
2. The ionization chamber is placed behind the collimator at a distance of 0.5 cm. This makes it possible to measure the photon beam dose behind the collimator and to control the correlation between the scanning of electron beam and the scanning of collimator.

In this "new geometry", the water phantom was added in at a distance of 40 cm from the collimator. The water absorbed dose was calculated in the voxels of this phantom at a depth of between 1 and 1.5 cm.

The DOSXYZnrc code was used for calculating dose distribution in further simulations. This code is an EGSnrc-based MC simulation code for calculating dose distributions in a rectilinear voxel phantom.

A "Parallel Circular Beam with 2-D Gaussian X-Y Distribution" was used as the source type of incident electron beam in the BEAMnrc code. The value of FWHM of the Gaussian distribution was set to 1 mm. The energy of electron beam was set to 6 MeV.

Three types of collimators were simulated with BEAMnrc code in this part of project: The phase space files that were generated for these collimators in BEAMnrc, were used as source input data for the DOSXYZ code. Parameters of these collimators as well as results for FWHM and PM of the obtained photon beam are given in Table 4 and in Fig. 5.

Simulated dose distribution of an intensity modulated field

A program was written that allowed us to determine the required intensity of each single beam, when single beams are moved in a raster-scan motion across a given field size to arrive at a desired dose distribution. The intensity weights are optimized in such a way that the obtained superimposed dose distribution matches a given input distribution of intensity.

The single photon beam profile was expressed as a 15 × 15 matrix, each element representing the dose at isocenter distance in a 1 × 1 mm pixel element. The raster scanning was performed in a quadratic point raster with 1 mm spacing.

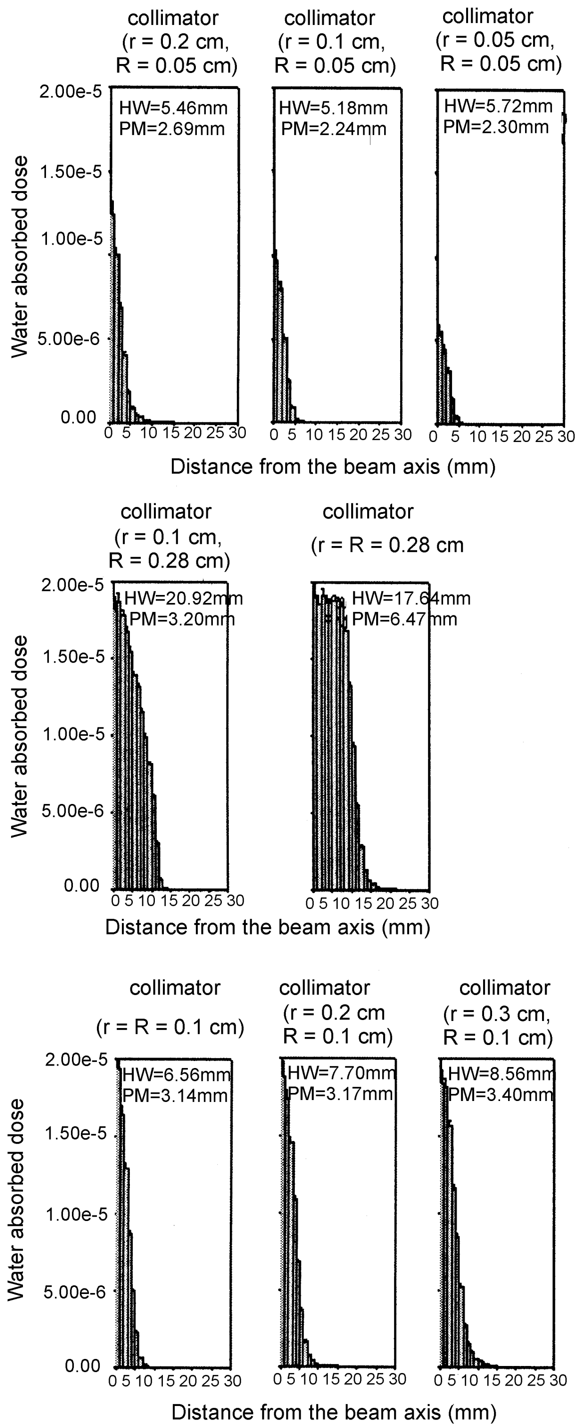

Fig. 3. Photon beam profiles for different collimators. HW and PM mean the full width at half-maximum and penumbra of beam profile, respectively.

Results

The dose distribution calculated for different collimators is presented in Table 1 and in Fig. 3. FWHM and PM express the full width at half-maximum and the penumbra of beam profile, respectively.

The best value for the width at half-maximum was for collimators #3, 6, 7, and 8, but for the last three of these, the dose was very small (see Fig. 3).

Influence of target construction

Figure 4 shows the comparison of photon beam profiles for different electron beam diameters and for three types of target construction. In the first model, 0.965 mm of gold, the cooling system and a layer of carbon was used in the second, air was used instead of carbon. For the third type, a small electron beam radius r_e equal to 0.5 mm was used, and in the fourth type the layer of gold was reduced to 0.5 mm. The best result, i.e. the most distinct forward direction for the water-absorbed dose to the beam axis was obtained for the fourth target, using the thin layer of gold.

However, the thickness of the gold target at the entrance to the collimator also influences the mean energy of the photon beam, as calculated. Calculations

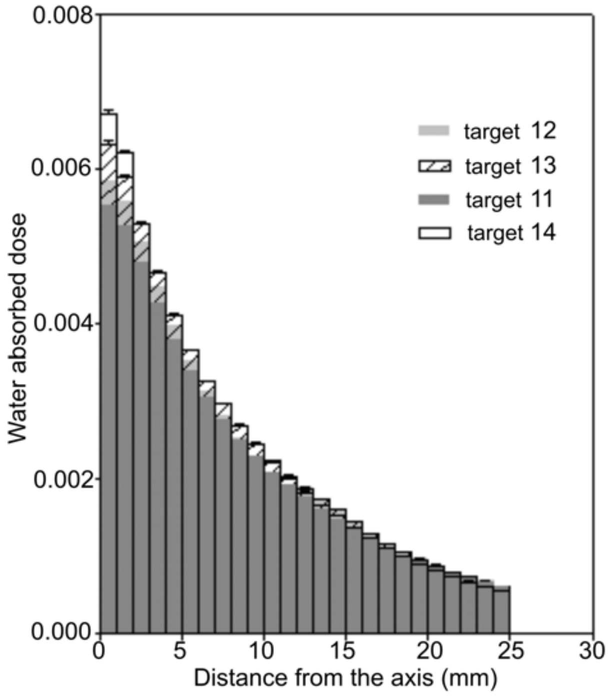

Fig. 4. Comparison of the water absorbed dose after target and ionization chamber for the different target construction and different size of electron beam: target 1 – r_e = 1 mm, 0.96 mm of Au and C in the target; target 2 – r_e = 1 mm, 0.96 mm of Au, air instead of carbon in the target construction; target 3 – r_e = 0.5 mm, 0.96 mm of Au, air instead of carbon in the target construction; target 4 – r_e = 0.5 mm, 0.5 mm of Au, air instead of carbon in the target construction.

Table 2. FWHM and PM of photon beam profile calculated for different collimators and different radius of incident electron beam (EB)

Number of collimator	Radius of EB (mm)		Radius of EB (mm)	
	1.0	0.5	1.0	0.5
	FWHM (mm)		PM (mm)	
#3	6.56	7.42	3.14	1.68
#4	7.70	8.20	3.17	2.07
#5	8.56	8.76	3.40	2.33

Table 3. Mean FWHM, PM and maximum dose (D_{max}) of the photon beam profile for different energy and r_e of incident electron beam

Collimator #3	Energy (MeV)		Energy (MeV)		Energy (MeV)*	
	6.174–7.103	4	6.174–7.103	4	6.174–7.103	4
	FWHM (mm)		PM (mm)		D_{max} (MeV/g)	
r_e = 1 mm and carbon	6.56	6.16	3.14	3.35	1.93e-5	8.86e-6
r_e = 0.5 mm and carbon	7.42	7.04	1.68	1.99	1.78e-5	9.34e-6
r_e = 0.5 mm and air	7.54	7.10	1.70	1.75	2.02e-5	9.43e-6

* D_{max} values are very small because they describe the dose of radiation associated with only a single electron. For example a dose of 2 Gy/min will require just 2.4 μA of electron current.

Table 4. FWHM and PM of beam profile calculated for different collimators

Size of collimator in z direction	Circular aperture r (mm)	Rectangular aperture r' (mm)	FWHM (mm)	PM (mm)
10	0.5	–	5.42	2.64
15	1.0	–	7.16	2.56
10	–	0.5	5.80	2.70

were performed for r_e = 0.5 mm for an energy spectrum of electrons from 6.174 to 7.103 MeV.

A calculation was also performed at SSD, with an r_e = 0.5 mm and a collimator with $r = R = 1$ mm when air instead of carbon was used in the target construction. Changes of FWHM and PM were: 7.42 and 1.68 mm (with carbon) and 7.54 and 1.70 mm (with air). An alternative method to reduce scattering material by reducing the thickness of gold foil appears less appropriate: when the thickness of the foil is reduced, a significant reduction of the mean photon energy is obtained.

Influence of the incident electron beam characteristics

Size of electron beam

Two values of the radius of electron beam, 1 and 0.5 mm, were selected. Results on FWHM and PM are presented in Table 2. The absorbed dose was calculated for collimators #3, 4 and 5.

It can be seen from Table 2 that a reduction in the radius of electrons r_e from 1.0 to 0.5 mm gives only a small increase in FWHM; however, it considerably improves the penumbra.

Energy of the electron beam

Absorbed dose for collimator #3 was calculated for two sets of electron energy: a spectrum from 6.174 up to 7.103 MeV and monoenergetic electrons of 4 MeV. Results are presented in Table 3.

Displacement of the electron beam

When the electron beam is forced to follow the moving collimator, it may not always conform to the aperture of the collimator. Therefore, we simulated a possible displacement of the electron beam from the axis of the target-collimator system. This simulation was done only for collimator #3 and a parallel beam with r_e = 0.5 mm. The possible displacement was simulated by:

a) parallel displacement of the electron beam of 0.5 mm from the system z axis in x direction, and
b) tilt of electron beam direction of 0.5° from the z axis.

FWHM at a distance of 40 cm from the collimator was used to determine possible influence, however this simulation resulted in no changes in the parameter.

Influence of collimator geometry

Table 4 compares the profiles of the photon beam, when it is calculated for three different collimators: (1) a 10 cm long collimator with a circular aperture of 0.5 mm, and (2) a 15 cm long collimator with a circular aperture of 1 mm and (3) a 10 cm long collimator with a rectangular aperture of 0.5 mm.

Field dose distribution of the photon beam was calculated for the two 10 cm collimators, and the one calculated for the collimator with a circular aperture is presented in Fig. 5.

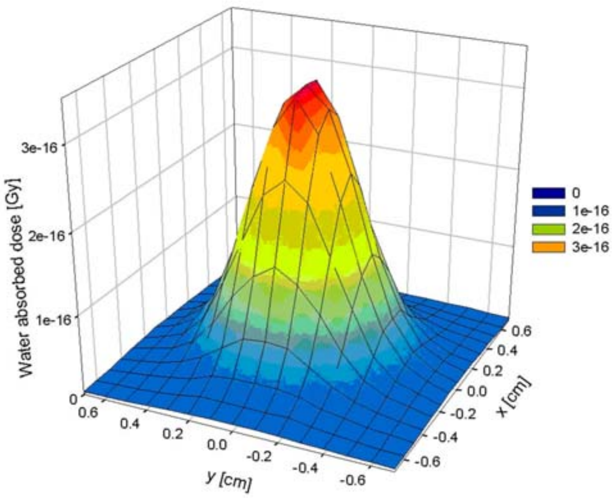

Fig. 5. Field dose distribution for the photon beam from the collimator with circular aperture of 1 mm; the electron beam diameter was 1 mm.

Simulated dose distribution of an intensity modulated field

An example of resulting dose distribution is shown in Fig. 6, right. The optimization procedure provided an individual, positive weight (intensity) for each raster point.

It might be useful to limit the variation of the weights between a maximum weight and a minimum weight. If a factor of 20 is introduced ($w_{min} = w_{max}/20$), the result of Fig. 7 is obtained.

This shows that the very small dose area is not "painted" correctly. A factor of 40, however, would be sufficient. In Fig. 8, four intensity profiles are compared. This comparison again demonstrates that in a larger area of reduced dose (in a "hole") the selected limitation of $w_{min} = w_{max}/20$ would lead to a too big reduction, whereas a factor of 40 obviously is sufficiently wide.

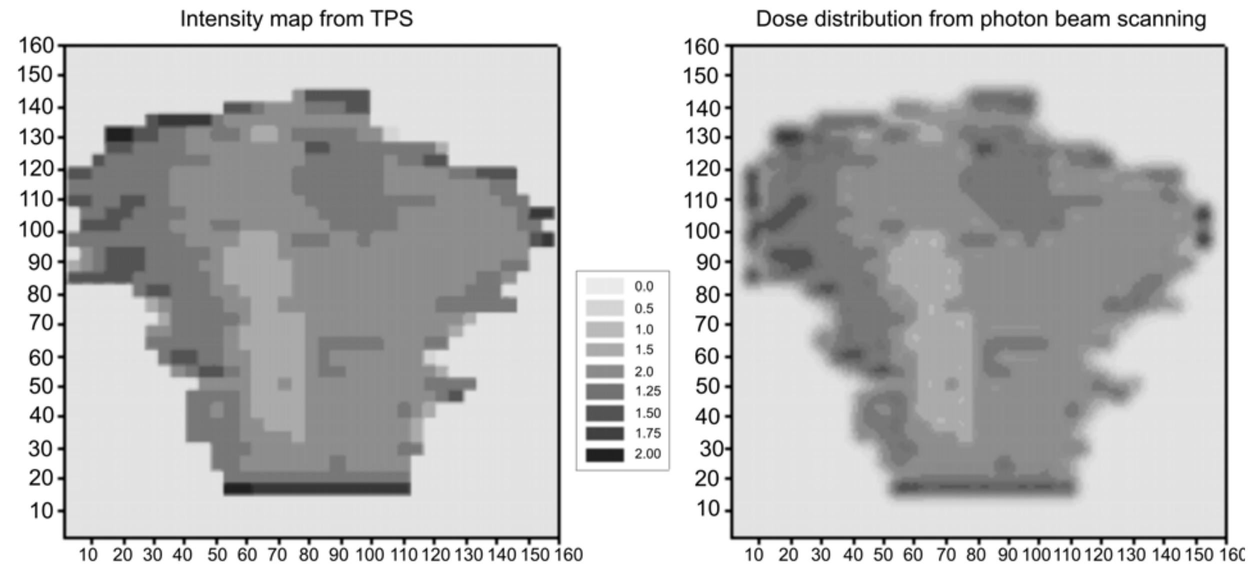

Fig. 6. Left – example for a desired intensity map as obtained from the treatment planning system. Right – dose distribution as obtained from a raster-scan with single photon beams, each produced by the target-collimator system with a dose distribution as shown in Fig. 5 (collimator with a circular aperture of 1 mm; electron beam diameter 1 mm).

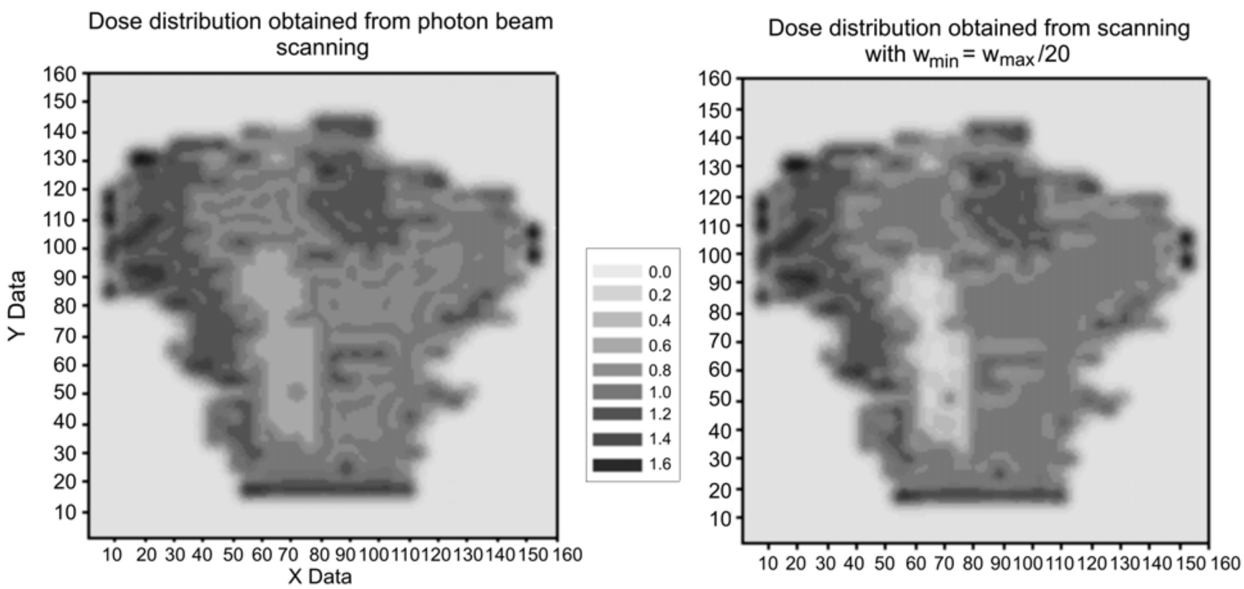

Fig. 7. Left – identical to Fig. 6 right. Right – $w_{min} = w_{max}/20$.

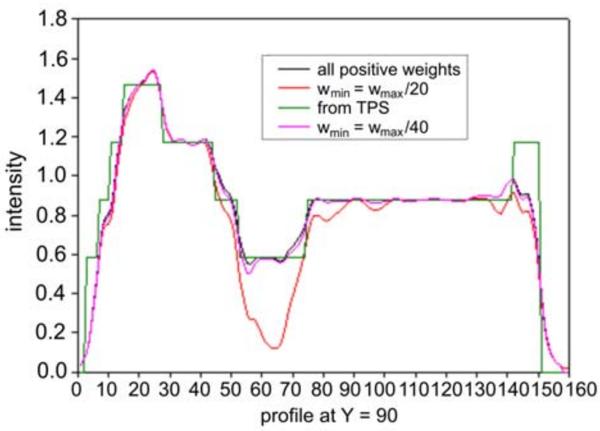

Fig. 8. Comparison of intensity profiles at $Y = 90$.

Conclusions

An optimal system of target-collimator-monitor for a scanning photon beam should have the following characteristics. First, the diameter of the incident electron beam should be smaller than 2.0 mm because when diameter of the electron beam is reduced, an improved penumbra of the photon beam is observed. Second, the energy of the electron beam should be not less than 6 MeV, because the intensity of the photon beam substantially decreases with decreasing energy, and using lower energy is, therefore, of no advantage. Third, using gold foil with a thickness of ~ 1 mm is an appropriate target, and avoids the need for any additional material. The mean energy of the photon beam decreases with foil thickness, which contributes to scattering.

Fourth, since the photon beam profile produced directly from the target is quite large, photon beam intensity after the collimator should increase with an increasing collimator entrance opening. This, however, produces an undesired effect on the photon beam profile after the collimator. Therefore, the collimator should have a non-divergent aperture with a diameter of ~ 1 mm. This aperture is necessary in order to obtain a photon beam diameter not larger than about 5 mm in the isocenter distance. A quadratic-shaped aperture would be better than a circular-shaped one, if a variable opening is to be constructed.

Fifth, the radiation monitor chamber must be placed behind the collimator, because any changes in photon beam intensity behind the collimator must be directly monitored. Sixth and finally, in respect to geometry, the distance between the beam exit at the radiation monitor and the isocenter should be not larger than 40 cm. This is because any increase in the distance between the collimator and isocenter will contribute to an increase in the photon beam diameter. A minimum diameter not larger than about 5 mm in the isocenter distance should be provided.

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