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ARTICLE

Radiation protection studies for a new mobile electron accelerator for intra operative radiation therapy (IORT)

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A specially constructed highly-mobile electron accelerator for intraoperative radiation therapy (IORT) is under development in Poland. Using an accelerator in a regular operating room (OR) for direct irradiation of surgically exposed organs raises specific questions concerning radiation safety of the patient and medical personnel. Therefore, the aim of this investigation was to optimize the beam forming system and external shields in order to assure radiation safety. The Monte Carlo code BEAMnrc/EGSnrc was used to build and test a model of the accelerator treatment head and beam applicators. We used FLUKA code to study the dose distribution inside and outside the OR. It was determined that dose distribution in the patient plane meets existing radiation protection requirements. It was further found that safe operation of the accelerator in a conventional OR may require some additional light shielding, depending on details of the wall construction, patient workload and occupancy factors. We show that relatively light and mobile lead shielding panels may be successfully used for that purpose.

Keywords: medical accelerator; IORT; Monte Carlo; dose distributions; shielding design

1. Introduction

Intraoperative radiation therapy (IORT) delivers a large single fraction dose of electron radiation to a surgically exposed tumor or tumor bed. In the past, electron beams from conventional linear accelerators were used in IORT, which required that the patient be transferred after surgery to a shielded radiotherapy room for irradiation. In recent years, the first mobile electron accelerators dedicated for IORT were developed, allowing the procedure to take place in the OR itself [1-4]. A specially constructed highly-mobile electron accelerator for IORT of this type is currently under development in our Institute.

Our study of two model treatment head assemblies for this IORT accelerator were described in a previous article [5]. The first ("plastic") model was characterized by a single scattering foil, without heavy collimators, and plastic applicators. The second ("metal") model incorporated a more complex system of scattering and flattening foils fitted into a set of heavy collimators, and metallic applicators.

In this paper we describe a "universal metal" treatment head that can connected to applicators with either a soft or hard–docking system, with new parameters and materials in comparison with those described in the previous paper.

Using an accelerator in a regular operating room (OR) for direct irradiation of surgically exposed organs raises specific questions concerning radiation safety of the patient and medical personnel. Therefore, the aim of this investigation was to optimize the beam forming system and external shields in order to assure radiation safety.

Our secondary objective was to assess the risk related to generation of neutron leakage radiation when applying electron beams with energies higher than 10 MeV.

2. Materials and methods

The Monte Carlo code BEAMnrc/EGSnrc was used to build and test a model of the accelerator treatment head and beam applicators [6,7]. Using this code, we optimized the collimators, foils and applicators construction in order to fulfill regulatory requirements concerning leakage radiation. The design of the therapeutic head allows for either "soft" or "hard" docking of an applicator. **Figure 1** shows the model of the treatment head and explains both docking schemes. We used FLUKA code to study the dose distribution inside and outside the OR [8,9]. To assess the risks related to exposure to leakage radiation, we modeled a hypothetical suite consisting of an OR and a Control Room, as illustrated in the **Figures 2** and **3**. We assumed 10 cm thick concrete walls and a 30 cm thick concrete floor and ceiling. We performed calculations without

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any additional shielding, as well as, with a lead shielding plate of dimensions 140 x 150 cm^2 and variable thickness, designed to protect the personnel in the control room. We analyzed dose levels in several locations inside and outside the suite as indicated. The points indicated in Figure 2 were located 1 m above the floor and 30 cm from the walls. The points indicated in Figure 3 are located on the beam axis.

2.1. Details of the accelerator treatment head

The accelerator we are developing will deliver electron beams in an energy range of 4 – 12 MeV. Thin-walled metal applicators with diameters 3 – 12 cm (and possibly larger at lower energies) can be attached to a universal therapeutic head (system of collimators and scattering foils independent of beam energy and applicator diameter) either using "soft" or "hard" docking. (see Figure 1)

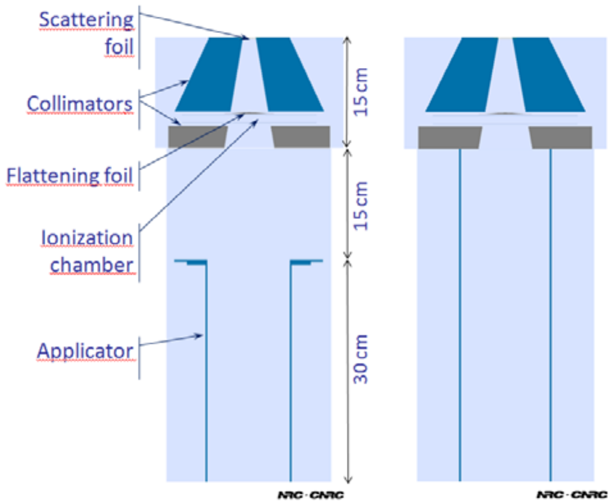

Figure 1. Accelerator treatment head with the soft-docking (left) and hard-docking (right) systems of connection with applicators.

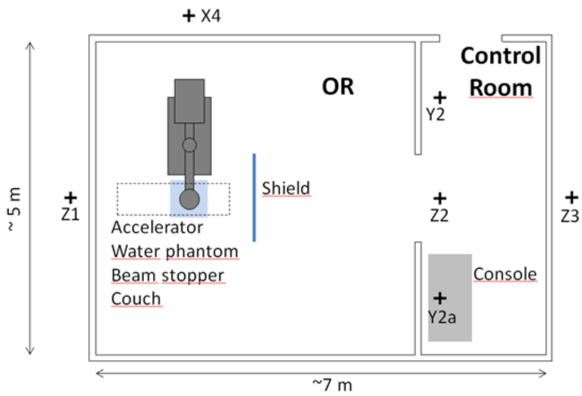

Figure 2. Layout of the OR and Control Room. The points selected for detailed dose analysis are indicated with the sign „+" (top view- x, y axis).

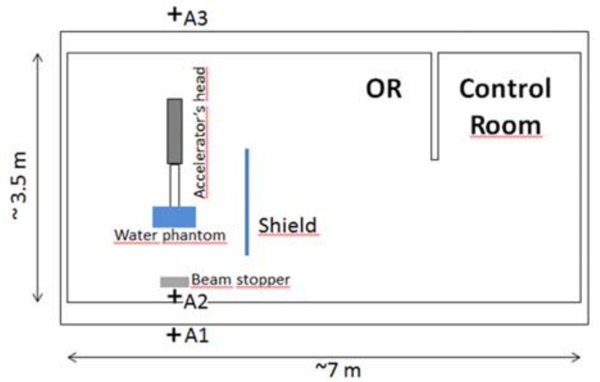

Figure 3. Layout of the OR and Control Room. The points selected for detailed dose analysis are indicated with the sign „+" (side view- y, z axis).

A double foil scattering system was designed to minimize energy loss of the beam and brehmsstrahlung production. Weight and shape of collimators were optimized and different applicator materials were studied. The treatment head is compatible with non-cylindrical applicators.

2.2. Monte Carlo simulation

2.2.1 BEAMnrc/EGSnrc simulations

This study used the EGS system, version V4-r2-2-5, for MC simulation with the user code BEAMnrc, version 2007 [6,7]. Simulations were performed for monoenergetic electron beams ranging from 4 to 12 MeV.

An electron beam with a Gaussian-distributed intensity profile of 3 mm full-width-half-maximum (FWHM) was directed onto the front of an accelerating structure vacuum exit window, through which it was transported to the treatment head and applicators. To assure statistical accuracy, these simulations were performed using 10^8 source particles. Transport parameters included an electron lower energy cut-off ECUT and AE of 0.7 MeV and photon lower energy cut-offs PCUT and AP of 10 keV.

Details of the calculation method and the MC code parameters used are similar to those described in an earlier article [5].

From the calculated percentage depth dose (PDD) in water, the following properties were determined: (a) depth of the maximum dose d_{max}, (b) depths of the 90% dose levels above and below the depth of maximum dose $d_{90\%}$, (c) depths of the 50% and 80% dose levels $d_{50\%}$, $d_{80\%}$, and (d) the relative dose due to bremsstrahlung (stray radiation).

From the beam profiles calculated in water, the following properties were determined: (a) beam flatness $(D_{max}- D_{min})/D_{min}$ x 100% in the central 80% of the beam field at d_{max}, (b) position of the field edge ($d_{50\%}$) at d_{max} and (c) distance from the field edge to $d_{90\%}$ ($d_{90\%}$-$d_{50\%}$) at the depth of maximum dose.

2.2.2 FLUKA simulations

MC simulations using FLUKA code, version 2.13 (2011), were performed to study radiation leakage in the operating room and to test the shielding of the entire system [8,9].

Simulations were performed for monoenergetic electron beams at energy ranging from 4 to 12 MeV. Calculations of beam transport started at a point located 1 mm above the first cell of the copper accelerating structure model (the FLUKA program does not facilitate simulation of charged particle dynamics under an RF field in a resonant cavity). The primary electron beam of 0.3 mm FWHM and divergence of 4 mrad is transported via c. 90 cm of vacuum inside the linear accelerator model and up to the titanium vacuum window, where beam size reaches FWHM of 3.6 mm, a size similar to that found under working conditions. Such beams were used to calculate the dose equivalent of radiation delivered at and around the patient plate, in order to determine how well the designed system meets operating standards. To assure statistical accuracy in a reasonable calculation time, these simulations were performed using $10^6 – 10^9$ source electrons.

3. Results and discussion

3.1. Dose outside treatment field

Therapeutic beam properties calculated for different energies and applicator diameter of 12 cm are summarized in **Table 1**.

Table 1. Therapeutic beam properties calculated for different energies and applicator diameter of 12 cm.

Input energy [MeV]	R_p [cm]	$E(R_p)$ [MeV]	d_{max} [cm]	$d_{90\%}$ [cm]	$d_{80\%}$ [cm]
4	1.6	3.4	0.7	0.9	1.0
6	2.6	5.4	1.1	1.5	1.7
9	4.1	8.4	1.8	2.5	2.8
12	5.6	11.4	2.3	3.5	3.9

R_p is the practical electron range in water, $E(R_p)$ is the nominal electron energy calculated using the R_p value, d_{max} ,$d_{90\%}$, $d_{80\%}$ are the depths of the maximum dose, 90% isodose and 80% isodose.

For both docking systems, we simulated the dose delivered outside the treatment field, stray radiation in the treatment field and leakage, both around the end of applicator and through the side wall. The calculated results for both docking systems were the same, within the statistical error. Calculations were performed for initial beam energies ranging from 4 to 12 MeV and for circular applicators with diameters ranging from 3 to 12 cm. **Table 2** and **Table 3** show sample results of these calculations (for an applicator diameter of 12 cm) in comparison with the limits recommended by the European Standard of International Electrotechnical Commission, IEC 60601-2-1 [10].

Table 2. Stray radiation at a depth of 100 mm beyond R_p, calculated for the applicator diameter of 12 cm.

Input energy [MeV]	4	6	8	10	12
IEC standard [%]	3.45	3.75	4.05	4.35	4.55
Results [%]	0.13	0.17	0.24	0.30	0.39

Table 3. Leakage radiation on the patient plate, calculated for the applicator diameter of 12 cm.

Maximum dose in the area between a line 2 cm outside the periphery of geom. field and the boundary of M_{10}					
Input energy [MeV]	4	6	8	10	12
IEC standard [%]	10	10	10	10	10
Results [%]	0.08	0.10	0.53	1.37	1.62
Average dose in the area between a line 4 cm outside the periphery of geom. field and the boundary of M_{10}					
Input energy [MeV]	4	6	8	10	12
IEC standard [%]	1	1	1	1	1.06
Results [%]	0.02	0.02	0.21	0.68	0.83

Leakage radiation at a distance of 1 m from the beam axis was calculated for both docking systems and compared with the maximum absorbed dose on the beam axis for the 12 cm diameter applicator. These values were less than 0.05 %, i.e. about 10 times below the recommended limit.

3.2. Dose equivalent inside and outside operating room

Two-dimensional distribution of relative dose equivalents inside and outside the operating room (OR) were calculated specifically for a maximum beam energy of 12 MeV and a 12 cm diameter applicator, without (**Figures 4a** and **b**) and with (**Figures 5a** and **b**) additional lead shielding. A dose of 20 Gy delivered to a patient over a single treatment, assuming three treatments per week, would result in a dose equivalent of about 0.03(2) mSv/year in the room above the OR and 1.1(2) mSv/year in the space directly beneath the floor of the operating room. Both of these results are equal to or less than the annual limit of 1 mSv for noncontrolled areas. A different situation was found behind the two concrete walls (10 cm) of the modeled OR. At points Z1 and X4 the dose equivalent was equal to 11.54(4) and 4.22(2) mSv/year, suggesting that it would be necessary to limit the presence of people there or improve the wall protection at these points.

We determined the dependence of dose equivalent from all particles (DEQ) and dose equivalent from neutrons only (neutron DEQ), at points Y2,Y2a, Z2, Z3 for energies 12 and 9 MeV, with a 12 cm diameter applicator, with different lead shielding thickness. **Table 4** shows sample results of these calculations at location labeled “Y2a”, i.e. in a place inside the control room where the control console could be located and thus it is a place where a technician works during patient irradiation.

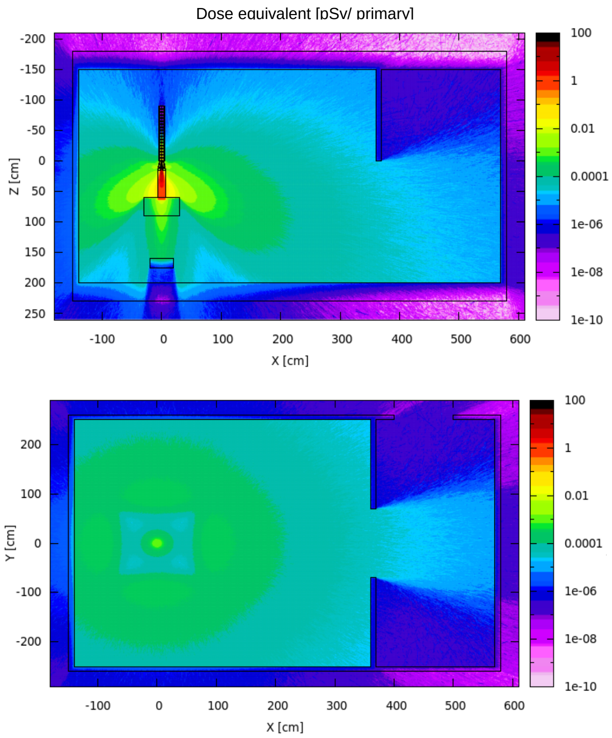

Figure 4. Two-D distribution of relative dose equivalents inside and outside the operating room were calculated for a maximum energy of 12 MeV, with a 12 cm diameter applicator without any shielding. Spatial dimensions (X, Y and Z axis) are in cm. (a) side view (b) top view.

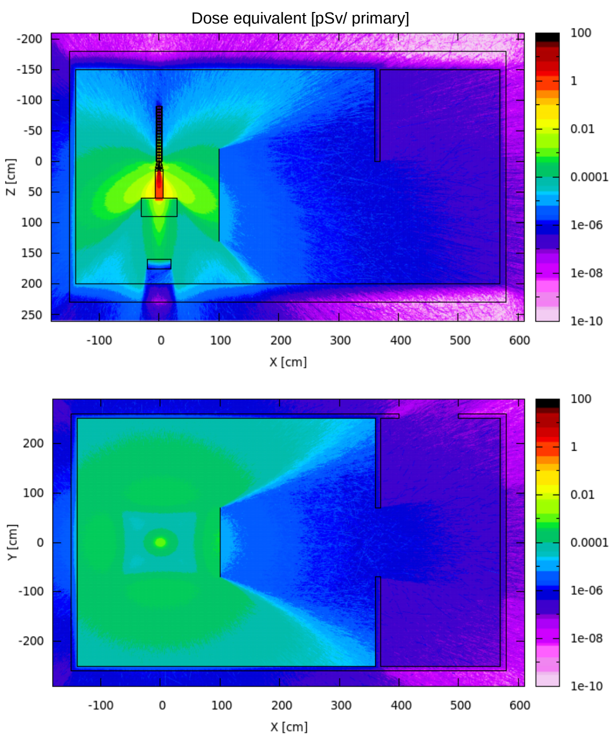

Figure 5. Two-D distribution of relative dose equivalents inside and outside the operating room were calculated for a maximum energy of 12 MeV, with a 12 cm diameter applicator with the shielding. Spatial dimensions (X, Y and Z axis) are in cm. (a) side view (b) top view.

Table 4. Dose equivalent from all particles and dose equivalent from neutrons only, calculated in the point Y2a for energies 12 and 9 MeV, with a 12 cm diameter applicator, with different lead shielding thickness.

Lead shielding [cm]	12 MeV		9 MeV	
	DEQ [mSv/y]	Neutron DEQ [mSv/y]	DEQ [mSv/y]	Neutron DEQ [mSv/y]
0	1.98(4)	0.0878(8)	1.99(4)	0.00039(2)
1	0.93(2)	0.0860(7)	0.96(2)	0.00035(2)
2	0.67(3)	0.0829(7)	0.65(2)	0.00036(2)
3	0.44(2)	0.0809(6)	0.428(9)	0.00036(2)
4	0.37(2)	0.0804(5)	0.316(8)	0.00031(2)
5	0.32(2)	0.0779(6)	0.252(5)	0.00030(2)

3.3. Dose equivalent from neutrons

We also used FLUKA calculations to estimate annual dose equivalent from neutrons beneath the floor of an operation room. In case of 12 cm applicator, at 12 or 9 MeV beam energy, assuming three treatments per week at 20 Gy per treatment, the doses would be 0.0062(6) and 0.00006(9) mSv/year. **Figure 6 a), b)** shows two-dimensional distributions of relative dose equivalent from neutrons, inside and outside the operating room. The main source of neutrons is the beam stopper made of lead with dimensions of 40cm × 40cm × 15cm (x,y,z).

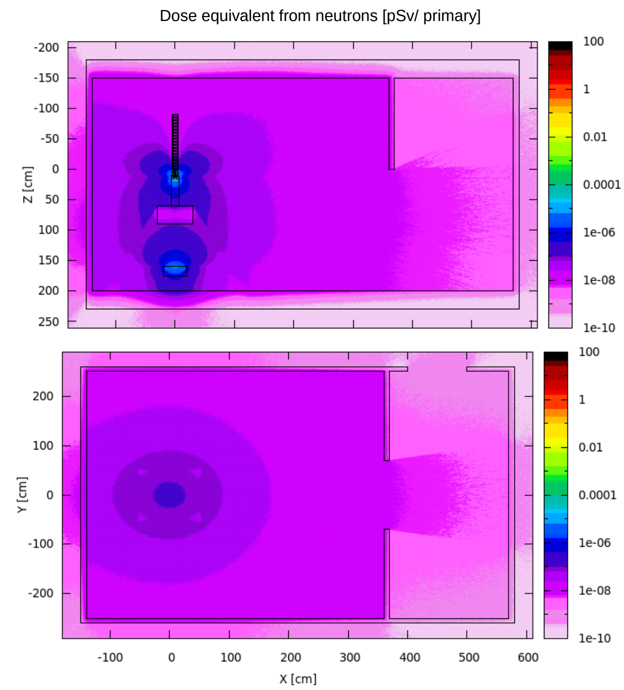

Figure 6. Two-D distributions of relative dose equivalent due to neutron radiation inside and outside the operating room calculated for a maximum energy of 12 MeV with a 12 cm diameter applicator. Spatial dimensions (X Y and Z axis) are in cm. (a) side view (b) top view.

4. Conclusions

Usage of an electron accelerator inside a regular OR is not a trivial issue in respect to radiation dose. In this work, we showed that the accelerator operation is possible without compromising the radiation safety of the patient and medical staff.

The new IORT accelerator will be built so that dose distribution in the patient plane meets existing radiation protection requirements.

Investigation of leakage and scatter radiation provides a resource to evaluate shielding and to set some limit on the number of IORT procedures performed weekly in an operating room. Assuming three treatments per week in certain OR, the cumulative yearly dose outside the OR would be well below the annual limit of 1 mSv for non-controlled areas in the locations above and under OR.

The walls (10cm concrete) of OR close to the points Z1 and X4 need additional protection (metal) if the rooms behind them are occupied during the treatments. To protect people working in the control room, it would be sufficient to use a mobile lead shield with a size of 1 x 140 x 150 cm (x,y,z) located between the accelerator and the control room.

Dose equivalent from neutrons are very low. In the control room these are 0.086 and 0.0003 mSv/y at 12 and 9 MeV electron beam energy, respectively.

It must be recognized that the above calculations are reasonable estimates only and that actual measurements should be performed after installation of the accelerator to assure safety of patients and personnel.

Acknowledgements

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