# A MONTE CARLO INVESTIGATION OF THE INFLUENCE OF INITIAL ELECTRON BEAM CHARACTERISTICS ON THE ABSORBED DOSE DISTRIBUTIONS OBTAINED WITH A 9 MEV IORT ACCELERATOR

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*A fost investigată influenţa caracteristicilor fascicului iniţial de electroni asupra distribuţiilor de doză absorbită obţinute cu un accelerator liniar mobil conceput pentru radioterapie intraoperatorie. Rezultatele arata că profilurile de doză depind de divergenţa fasciculului iniţial, în timp ce parametrii energetici influenţează distribuţiile dozei in profunzime.*

*The influence of initial electron beam characteristics on the absorbed dose distributions for electron beams obtained with a mobile linear accelerator designed for Intraoperative Radiation Therapy has been investigated. Results show that the transverse dose profiles are sensitive to the divergence of the initial beam, while the energy parameters influence the depth-dose distributions.*

**Keywords:** IORT, electron linear accelerators, dose distributions, Monte Carlo.

## 1. Introduction

The Intraoperative Radiation Therapy (IORT) is a specialized irradiation technique which allows delivering a single high radiation dose (20 – 25 Gy), during the surgical intervention, after the resection of the visible tumour [1]. The advantages of the IORT technique are multiple: (a) the prescribed dose is delivered directly to the tumour bed in which, after the surgical intervention, there is a higher probability to retrieve neoplastic cells that is, therefore, subject to greater risk of local recurrence, (b) the visual control of the target volume, (c) the possibility to protect healthy tissues by moving them away from the path of the radiation beam, and (d) the possibility to administrate a homogeneous dose to a selected layer of tissues surrounding the tumour. The IORT technique can also be used to irradiate the initial cancers of small volume or in unresectable

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malignancies for palliative purpose. To date, IORT has been used in the treatment of various malignancies. Local control has always been very high and the toxicity related to the methodology very low. Cancers of the stomach, pancreas, colon rectum and sarcomas, in which the local recurrence is the main cause of failure, have been the objects of numerous clinical studies. The long-term results confirm a positive impact on the local control that is generally associated with increased survival. New fields of application are the cancers of the breast, lung, bladder and uterine cervix [2].

Beginning with 1970, some radiotherapy centres from USA, Japan and Europe, started to perform IORT, by employing their conventional electron accelerator equipped with special applicators. IORT by means of conventional accelerators has two major disadvantages: (i) the movement of the patient during the operation from the operating theatre to the radiotherapy department, thereby necessitating extended anaesthesia time and, above all, exposing the patient to high risks during the transfer and (ii) the interruption activities in both departments for a prolonged period of time [3].

At the end of the 1990s, the first mobile accelerators dedicated to IORT have been manufactured: **Mobetron** (IntraOp Medical Incorporated, USA), **NOVAC7** (Hitesys, Italy) and **LIAC** (Info & Tech, Italy). These accelerators are relatively smaller and lighter and can be easily transported into the operating room, allowing to perform IORT without moving patients and with no structural modification of the operating room.

Mobile accelerators for IORT generate high energy electron beams ($3 \div 12$ MeV) and are equipped with cylindrical applicators of various diameters ($3 \div 10$ cm). The field sizes are given by the applicators diameter. The field having 10 cm diameter is considered as a *reference field*. The cylindrical applicators, usually made by polymethyl methacrylate (PMMA), can have an oblique distal part that is tilted with respect to the geometric axis of the beam, with angles ranging from 15° to 45° (base bevelled applicators). Depending on the length of the IORT applicators, the source to surface distance (SSD) for these accelerators can have values between 60 cm and 100 cm [3 - 5].

Monte Carlo methods have become an important auxiliary tool for the determination of clinical parameters in radiotherapy treatment planning and, particularly, for the radiation beam characterization. The main problem that must be solved in the process of Monte Carlo simulation of linear accelerators used in radiotherapy is the determination of the initial beam parameters (that is, of the beam incident on the accelerator exit window). Important parameters, such as spatial fluence distributions, angular divergences and energy spectra are not exactly known and usually are fixed using a "tuning" procedure involving repeated and time consuming simulations. The input parameters are progressively

modified, in order to obtain a satisfactory agreement between calculated and measured dose distribution in a water phantom.

Information regarding the determination of the initial electron beam characteristics used to simulate electron/photon beams generated by medical linear accelerators is rather limited. *Björk et al* [6] and later *Tzedakis et al* [7] investigated the influence of the initial electron beam characteristics on the absorbed dose distributions in a water phantom for radiotherapy electron and photon beams, respectively, in the case of *conventional* accelerators. Using the Monte Carlo method, in the case of the photon beams generated by a SL75/5 (Philips/Elekta) linear accelerator, *Tzedakis et al* [7] found that depth-dose and dose profile curves were considerably affected by the mean energy of the electron beam, with dose profile to be more sensitive to that parameter. The dept dose curves were unaffected by the radial intensity of electron beam. In contrast, dose-profile curves were affected by the radial intensity of initial electron beam for a large field size. No influence was observed in dose profile or depth-dose curves with respect to energy spread variations of electron beam. Somewhat similar, it is shown by *Björk et al* [6] that, in the case of some electron beams generated by a SL25 (Philips/Elekta) linear accelerator, the relative absorbed dose distribution (depth-dose and dose profiles) were insensitive to the geometrical parameters of the initial beams studied. The dose profiles were unaffected by the energy spectrum of the initial beam. However, they found that the energy spectrum of the initial beam has some influence on the depth–dose distribution. If the spectrum is symmetric (e.g., Gaussian) and the full with at half maximum (FWHM) is less than circa 10% of the most probable energy, the effect on the depth–dose curve is negligible. A larger FWHM will decrease the normalized dose gradient, but will not affect the dose in the build-up region. An asymmetric spectrum (e.g., wedge shaped) has the capability of simultaneously increasing the dose at depths smaller than $z_{max}$ (depth of maximum dose) and decreasing the dose gradient.

Data regarding the selection of parameters describing the incident electron beam are also presented in the references [8] and [9], but information about the influence of these parameters on the dose distributions for *IORT electron beams* cannot be found in the literature. Unlike non-dedicated linear accelerators used for conventional radiotherapy, the mobile IORT machines are equipped with long cylindrical applicators that have a larger contribution to the energy degradation, as well as to the spatial and angular distributions of the electrons at the phantom/patient surface, influencing the dose distributions. There are also significant differences between beams generated by different IORT accelerators. As we shown in a previous work [10], the contribution from the scattered electrons to the total dose was found to be up to 15% higher in the NOVAC7 IORT beams comparing to electron beams generated by a Philips/Elekta SL25 adapted for IORT [11].

In this paper, the influence of initial electron beam parameters on the absorbed dose distributions in a water phantom is investigated for 9 MeV electron beams generated by the NOVAC7 mobile linear accelerator dedicated to IORT. Several initial beams exhibiting different geometric properties and energy distributions are studied. The results are compared with those obtained by *Björk et al* [6] for electron beams generated by a conventional accelerator. The objective of this work is also to elucidate the influence of the IORT applicators on the absorbed dose distributions.

## 2. Materials and methods

### 2.1 Simulation of electron beams generated by the NOVAC7 IORT accelerator

The NOVAC7 system is a robotic mobile intraoperative electron beam unit. This accelerator produces pulsed electron beams with four different nominal energies: 3, 5, 7 and 9 MeV. The accelerator is equipped with a 3D movable arm that can be pointed on the operating field. The basic system includes four types of Perspex (PMMA) cylindrical applicators with inner diameters 4, 6, 8 and 10 cm, wall thickness 0.5 cm and lengths 69, 67, 67 and 87 cm, respectively. The source-to-surface distance (SSD) is 80 cm, except for the applicator with the diameter of 10 cm for which the SSD is 100 cm. There are no scattering foils or flattening filters inside the treatment head, as the spatial uniformity of the treatment field is obtained by the scattering processes of electrons on the applicator wall [12].

The geometry of the NOVAC7 IORT accelerator (i.e. all of the essential components in the treatment head) was built using BEAMnrc [13, 14], an EGSnrc [15] based general purpose Monte Carlo code originally developed for simulating radiotherapy beams from linear accelerators, X-ray or $^{60}$Co units. The accelerator was modelled as a series of simple BEAMnrc component modules with cylindrical symmetry centred on the *z*-axis (Fig. 1). The shape, dimension and material of these components were simulated according to the information provided by the manufacturer.
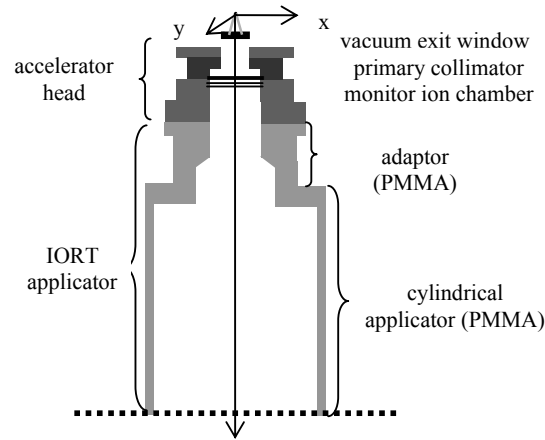
Fig. 1 The BEAMnrc model used to simulate the electron beams from the NOVAC7 accelerator (not to scale).

For comparison, 3D virtual models of NOVAC7 and of a conventional linear accelerator obtained using EGS_windows graphical package [16] are shown in Fig. 2. It is interesting to observe that the presence of the long IORT applicator will enhance the influence of the initial electron beam characteristics on the absorbed dose distributions.

The Monte Carlo calculations were also performed *without* any applicator (open beams) because, for this configuration, the characteristics of the IORT beams seems to be more directly related to the initial electron beams parameters [6, 10]. Additionally, comparing the results obtained with and without the IORT applicator the influence of this specific device on the absorbed dose distributions can be easily investigated.

For each simulated beam, the complete information (energy, position, direction, charge, etc.) about any particle that crosses a given plane perpendicular to the beam axis (scoring plane) was stored in a data file (the *phase-space* file) further used as input file for dose distributions calculations.

A number of eight IORT beams and the same number of open beams have been simulated using initial electron beams with various geometric and energy characteristics. The parameters of the initial electron beams are labelled in text with capital letters from A to H (see also Tables 1 and 2). In the case of the open beams, the applicator has been replaced by a layer of air in such a way that the source-to-surface distance was kept SSD = 100 cm. Like in the paper of *Björk et al* [6], the initial electron beam was the only free parameter in the model, while all other parameters, such as the simulation geometry and those for the radiation transport, were held unchanged.
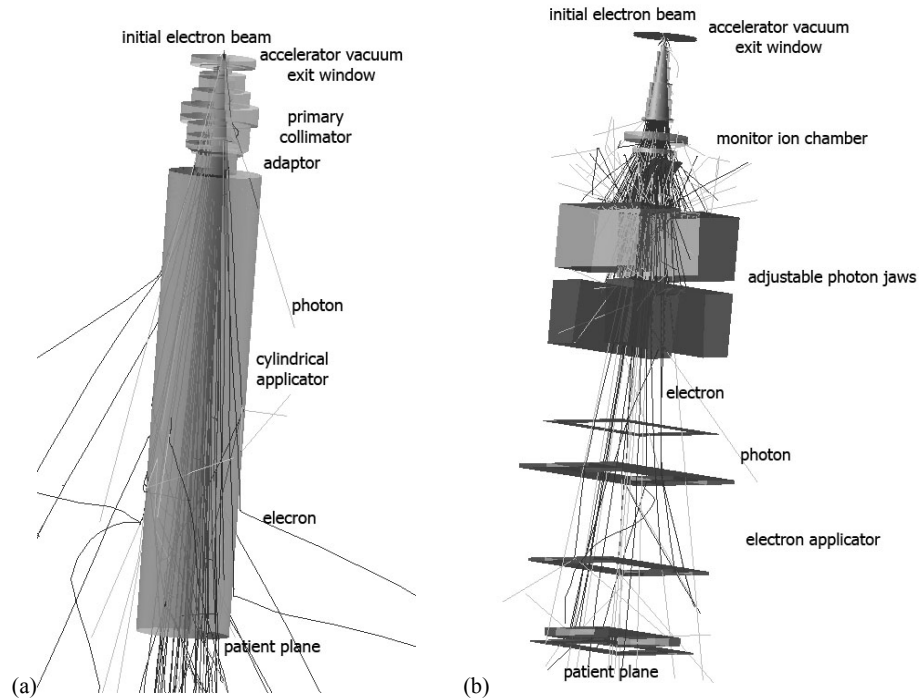
Fig. 2 Illustrations of NOVAC7 (a) and of a conventional linear accelerator (b) in EGS_windows. EGS_windows is a 3-D tool for interactively display the geometry of the accelerator and the track history for all different particles (photons, electrons and positrons) [16].

All simulations concerning the investigation of the geometric properties of the initial beam (A to D) were performed with monoenergetic 9 MeV incident beams, while E to H were pencil beams with different energy distributions. The first two energy spectra (E and F) are pure Gaussian, the other two (G and H) having "more realistic" spectral shape with low-energy components. The beam labelled G has 20% percent of the electrons in the low-energy tail, while the beam labelled H has 33% of the number of the electrons in this region. However, both initial electron energy spectra were adapted to have the same mean energy (9 MeV). These low-energy tails are typical for the NOVAC7 IORT accelerator. As stated by the manufacturer this low-energy component is not removed from the accelerator beam as no filtering system or bending magnets are present in this type of autofocusing accelerator [10].

Note that the area of initial beams onto the exit window of the accelerator was circular in all cases.

*Table 1*

**Geometric characteristics of the initial electron beams.**

| Beam index | Beam description | Beam size on the accelerator window |
|---|---|---|
| A | Pencil beam | 0 mm |
| B | Plane-parallel with uniform fluence distribution | Diameter 4mm |
| C | Isotropic point source with divergent cone angle 4 | Diameter 4mm |
| D | Plane-parallel with Gaussian fluence distribution | FWHM 4mm |

*Table 2*

**Energy characteristics of the initial electron beams: $E_{p,i}$ is the most probable energy, $\Gamma_i$ is the full with at half maximum (FWHM) also expressed as a percentage of $E_{p,i}$; $E_{min,i}$, $E_{max,i}$ and $\bar{E}$ are the minimum the maximum and the mean energy of the electrons form the initial beam, respectively;**

| Beam index | Spectral shape | $E_{p,i}$ [MeV] | $\Gamma_i$ [MeV] | $E_{min,i}$ [MeV] | $E_{max,i}$ [MeV] | $\bar{E}$ [MeV] |
|---|---|---|---|---|---|---|
| A | Monoenergetic | 9 | 0 | - | - | 9 |
| E | Gaussian | 9 | 0.45 (5%) | 8.40 | 9.60 | 9 |
| F | Gaussian | 9 | 1.35 (15%) | 7.50 | 10.50 | 9 |
| G | Gaussian with a low-energy component | 9.15 | 0.45 (5%) | 7.30 | 9.75 | 9 |
| H | Gaussian with a low-energy component | 9.30 | 0.45 (5%) | 6.60 | 9.90 | 9 |

In the BEAMnrc simulations both photons and electrons were transported down to 10 keV kinetic energies (ECUT = 0.521 MeV, PCUT = 0.01 MeV). The cross section data for all of the materials used in the simulations were obtained by the PEGS4 code [15] with AE = 0.521 MeV, AP = 0.01 MeV and density effect corrections from the International Commission on Radiation Units and Measurements [17].

The number of source electrons was $10^8$ for IORT beams and 2 x $10^8$ for open beams, which ensures enough particles in the forthcoming dose calculations.

### 2.1 Dose calculation

The stored phase-space files have been used as source inputs for the calculation of dose distributions in water phantom of Cartesian voxel geometry, using EGSnrc user-code DOSXYZnrc [18]. A 20 x 20 x 5 cm$^3$ water phantom was used for IORT beams, while for open beams a larger phantom (40 x 40 x 5 cm$^3$) was built.

Transverse dose profiles (crossplane direction) were obtained from the phase-spaces at depth of 2 cm for IORT beams and 2.1 cm for open beams (approximately depth of dose maximum for the two types of beams) The bin dimensions (crossplane × inplane × depth) of the dose computation grid for crossplane profile studies were set to 0.5 cm × 6 cm × 0.4 cm. The profiles were normalized to the mean dose over ±0.25 cm around the central axis of the beam.

Dose scoring grid for depth-dose curves were set to 1 cm x 1 cm x 0.1 cm, being normalized to the maximum registered dose value. All calculations have been done from phase-space files at SDD = 100 cm.

In DOSXYZnrc simulations we have used default values for EGSnrc particle's transport parameters, PRESTA-I for boundary crossing algorithm and PRESTA–II as electron transport algorithm. Both photons and electrons are transported down to 10 keV kinetic energies (ECUT = 0.521 MeV, PCUT = 0.01 MeV). The number of histories was 4 x $10^7$ for depth-dose curves and 10 x $10^7$ for transverse dose profiles, which ensures an excellent statistical uncertainty (mostly better than 0.2% (1 SD).

### 3. Results and discussion

*Transverse dose profiles* in water at SSD = 100 cm for open beams and IORT beams (applicator with diameter d = 10 cm) are shown in Fig. 3 and Fig. 4, respectively. In Figs. 3a and 4a the dose distributions curves are obtained for initial electron beams with different geometric properties (indexes A – D in Table 1), while in Figs. 3b and 4b the dose profile for the mono-energetic pencil beam (index A) is compared with those generated by the initial electron beams with different energy properties (indexes E – H in Table 2).

All profiles obtained for *open beams*, excepting that generated by the initial electron beam labelled C, are very similar in shape. Thus, transverse dose profiles for open beams (Fig. 3) have been found to be sensitive only to the divergence of the initial beam. Beam size, electron fluence and energy distributions have no influence on the lateral dose distributions when the IORT applicator is detached from the accelerator head.

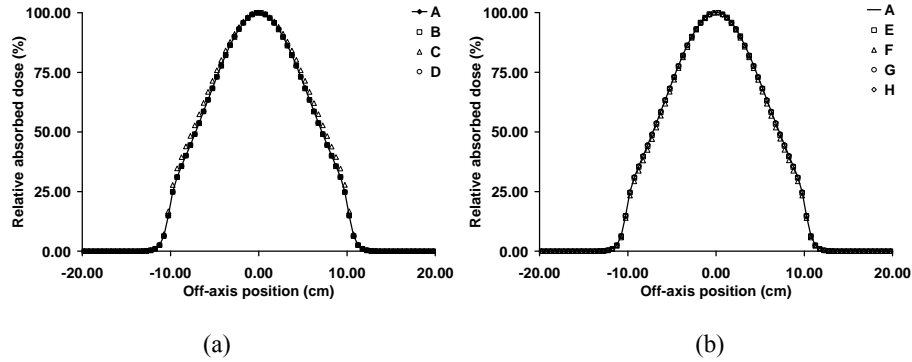(a)                                                          (b)

Fig. 3 Transverse dose profiles for *open beams* generated using initial electron beams with different geometric properties (a) and different energy spectra (b). The properties of each beam label are given in Tables 1 and 2. The statistical uncertainty (1 SD) of the simulated dose values is less than 0.2% for all values exceeding 20% relative dose.
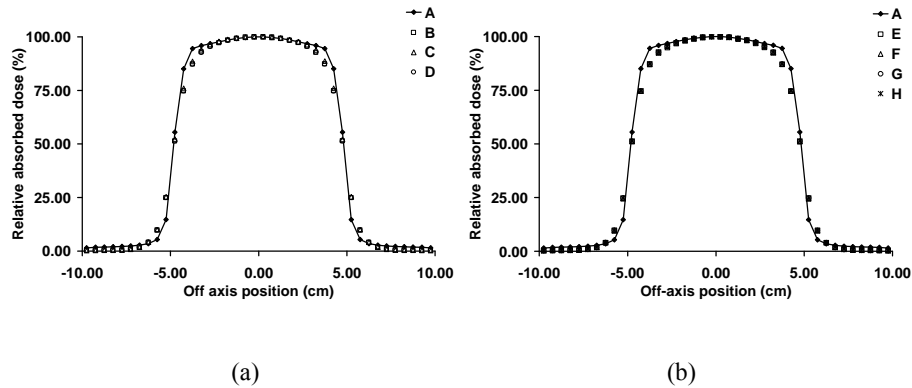


(a)                                                          (b)

Fig. 4 Transverse dose profiles for *IORT beams* generated using initial electron beams with different geometric properties (a) and different energy spectra (b). The properties of each beam label are given in Tables 1 and 2. The statistical uncertainty (1 SD) of the simulated dose values is less than 0.1% for all values exceeding 20% relative dose.

Attaching the IORT applicator, the shape of transverse dose profiles is severely changed (see Fig. 4 compared with Fig. 3). First of all, the radial extension of the dose distributions curves is reduced about two times, from approx. 20 cm to approx. 10 cm, at a depth of 2 cm in the water-phantom. Secondly, these curves become flattened in their central part. However, as in the case of the open beams, the transverse dose profiles for *IORT beams* are generally unaffected (with one exception) by the initial electron beams characteristics, at least within the studied intervals of the initial beam parameters. The exception is the mono-energetic pencil beam (index A) for which the lateral dose profiles are different from all the others, especially in the penumbra region where are registered relative dose values up to 10% larger.

Furthermore, the pencil beam give rise to dose distributions curves more flattened in their central region. This is an unexpected and hard to explain result, taking into account that any dose distribution is an outcome of the direct and scattered components of the beam (i. e. the electrons that after crossing the exit window interact only in air and in the monitor chambers and those electrons which interact with the accelerator head components and/or applicator) [10]. In the case of a theoretical (un-realistic) mono-energetic pencil beam, the direct component is relative larger compared with the scattered component. Because the direct component of the electron beam is more forward-directed, the lateral dose profiles should be less flattened, in contradiction with our results. To explain this contradictory behaviour of the transverse dose profiles, more detailed investigations are needed in the future.

Finally, even if the comparison between two different linear accelerators are not recommended, we still report some similarities between our results and those obtained by *Björk et al* [6] for a conventional accelerator. Excepting the pencil beam case discussed above, the transverse dose profiles for the NOVAC7 IORT accelerator have the same behaviour described in the above reference: they are not affected by the geometric and energy parameters of the initial electron beam, despite the long IORT applicator (see Figs. 1 and 2).

*Depth-dose curves* in water at SSD = 100 cm for different sets of initial beams are shown in Fig. 5 (open beams) and Fig. 6 (IORT beams). Labels A – D refer to the geometric parameters, while labels E – H denote different energy spectra of the initial electron beams (see Tables 1 and 2).

Comparing the Figs. 6a and 5a, we see that the depth-dose dose curves obtained with, as well as without applicator, are clearly *not affected* by the geometric properties of the initial electron beam. These results are similar with those obtained by *Björk et al* [6] for a conventional accelerator. Note that in the cited reference, there is no information about dose distributions generated without the IORT applicator (open beams).

Figs. 5b and 6b illustrate the influence of the energy distribution of the initial electron beam on the depth-dose distributions. Thus, in contrast with the results obtained for the geometrical parameters (Figs. 5a and 6a), the shape of depth-dose distributions obviously *depends* by the energy parameters of the initial beam (see Table 2). Compared with curve A (mono-energetic pencil beam), the most spectacular behaviour has the curve F which is obviously shifted toward higher depths, due to the extremely large FWHM of the initial energy spectra (15% compared with only 5% for all the other beams). The rest of the curves (E, G, and H) have almost similar behaviours in Fig. 5b (open beams) and Fig. 6b (IORT beams). In the build-up region, only the open beams exhibits somewhat higher dose values, but no more than 1%. For depths $z$ situated between $z_{max}$ (depth of maximum dose) and $R_{50}$ (the depth at which the absorbed dose reaches

50% of the maximum dose), all dose distributions, excepting that corresponding to the beam F, have the same shape and position. Beyond $R_{50}$, a larger FWHM ore a larger number of the electrons in the low energy "tail" of the initial beam will decrease the normalized dose gradient, but will not affect too much the $R_{50}$ value, an important parameter in the ionizing radiation dosimetry. Excepting the beam F, our results are only in partial agreement with those obtained by *Björk et al* [6], which have found more pronounced differences in the build-up region, especially when energy spectra having a low energy component where used.



(a)                                                                (b)
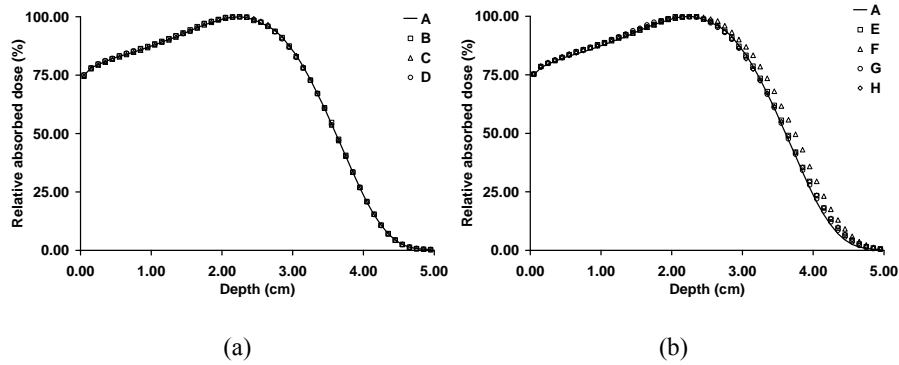
Fig. 5 Depth-dose distributions for *open beams* generated using initial electron beams with different geometric properties (a) and different energy spectra (b). The properties of each beam label are given in Tables 1 and 2. The statistical uncertainty (1 SD) of the simulated dose values is less than 0.4% for depths smaller than $z_{max}$ (the depth of maximum dose), being of maximum 2% for depths larger than $z_{max}$.



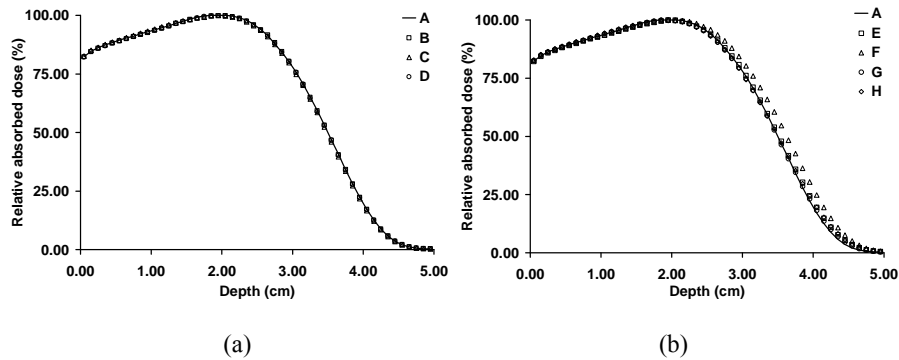(a)                                                                (b)

Fig. 6 Depth-dose distributions for *IORT beams* generated using initial electron beams with different geometric properties (a) and different energy spectra (b). The properties of each beam label are given in Tables 1 and 2. The statistical uncertainty (1 SD) of the simulated dose values is less than 0.3% for depths smaller than $z_{max}$ (the depth of maximum dose), being of maximum 2% for depths larger than $z_{max}$.

The Figs. 5b and 6b are very similar, demonstrating that the long IORT applicator has a minor influence on the manner in which the energy parameters of the initial electron beams influence the depth-dose distributions. However, this does not mean that the applicator has not any influence on these dose distributions.

Actually, attaching the long PMMA applicator, significantly larger values of the relative absorbed dose in the build-up region are obtained (i. e. for depth $z < z_{max}$ = depth of dose maximum). In our case, the surface dose is up to 10% larger in the case of relative depth-dose distributions for the IORT beams, compared with the open beams. In the same time, $z_{max}$ goes to the phantom surface up to 2 mm.

## 4. Conclusions

The influence of the initial electron beam characteristics on the absorbed dose distributions for electron beams generated by NOVAC7, a mobile linear accelerator dedicated to Intraoperative Radiation Therapy (IORT), has been studied using the Monte Carlo method. Our investigation has been performed for 9 MeV nominal energy on beams obtained with IORT applicator (10 cm diameter), as well as on beams obtained without any applicator (open beams). The NOVAC7 accelerator has been modelled using BEAMnrc code and the dose distributions in a water phantom (transverse dose profiles and percentage depth-dose curves) have been calculated with DOSXYZnrc. Different geometrical and energy parameters have been used for the initial electron beam source. We have found that only the transverse dose profiles for open beams are sensitive to a certain geometrical parameter, namely the divergence of the initial beam. The other geometrical parameters (such us beam size and shape, and electron fluence distribution) have no influence on any other dose distribution. The energy parameters (spectral shape, FWHM value, the weight of the low energy component from the energy spectra) influence only the depth-dose distributions curves. With some exceptions, our results are similar with those obtained by other authors for electron beams generated by a conventional accelerator. Even if in some cases the dose distributions are fairly independent on the initial beam characteristics, we can conclude that the Monte Carlo method is a powerful tool to find these characteristics which are usually fixed using a "tuning" procedure: the input parameters of the electron source are progressively modified, in order to obtain a satisfactory agreement between calculated and measured dose distribution in a water phantom. However, this is a time consuming procedure, involving repeated simulations. Taking into account the results obtained in this work, we recommend a relative short way to find the initial electron beam parameters. Firstly, the divergence of the beam is determined comparing only the calculated

and measured transverse dose profiles for open beams. Then, once the geometrical parameters of the beam are known, the energy characteristics of the initial electron beam can be determined by a similar procedure only for depth-dose distribution curves. It is the same "tuning" procedure but with less simulations.

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