Photon-beam subsource sensitivity to the initial electron-beam parameters

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One limitation to the widespread implementation of Monte Carlo (MC) patient dose-calculation algorithms for radiotherapy is the lack of a general and accurate source model of the accelerator radiation source. Our aim in this work is to investigate the sensitivity of the photon-beam subsource distributions in a MC source model (with target, primary collimator, and flattening filter photon subelements) to the electron subsource for 6- and 18-MV photon beams when the energy and radial distributions of initial electrons striking the linac target change. For this purpose, phase-space data (PSD) was calculated for various mean electron energies striking the target, various normally distributed electron energy spread, and various normally distributed electron radial intensity distributions. All PSD was analyzed in terms of energy, fluence, and energy fluence distributions, which were compared between the different parameter sets. The energy spread was found to have a negligible influence on the subsource distributions. The mean energy and radial intensity significantly changed the target subsource distribution shapes and intensities. For the primary collimator and flattening filter subelements, the distribution shapes of the fluence and energy fluence changed little for different mean electron energies striking the target, however, their relative intensity compared with the target subsource change, which can be accounted for by a scaling factor. This study indicates that adjustments to MC source models can likely be limited to adjusting the target subsource in conjunction with scaling the relative intensity and energy spectrum of the primary collimator, flattening filter, and electron subelements when the energy and radial distributions of the initial electron-beam change. © 2005 American Association of Physicists in Medicine.

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Key words: Monte Carlo simulation, photon beam, beam characteristics

I. INTRODUCTION

Monte Carlo (MC) methods have been used extensively in medical physics for modeling linear accelerators and for radiation therapy dose calculations.1−26 MC methods used for the latter purpose produce accurate results in the vicinity of tissue heterogeneities, such as air cavities and surface irregularities, and are considered the most accurate method for predicting dose distributions for treatment-planning purposes. Given the availability of fast radiotherapy-specific MC codes and ever-increasing computer speed, a major barrier to the extensive clinical implementation of MC dose calculations is the lack of a generalized source model of the accelerator radiation source. In particular, such a source model should allow a user with an arbitrary linear accelerator to commission an MC dose-calculation algorithm that meets a predetermined accuracy requirement (such as 2% or 2 mm27 or better) for patient dose calculations. A generalized source model that can be tuned to match the output of a general user’s accelerator is needed to overcome these limitations.

Several possible approaches are described and discussed in detail in previous publications.17,28 One approach of a source model is to characterize the beam analytically, as described by Jiang et al.29 and more recently by Fippel et al.30 A disadvantage of these source model types is their ability to model physically unreal conditions.29 Another approach is to perform full MC simulations of the radiation transport through the accelerator head.9,24 Thereby, phase-space data (PSD) is generated that contains the necessary data (position, momentum, energy, and charge) for each particle traversing the phase-space- (PS-) scoring plane. The PS plane is usually perpendicular to the beam axis and above the irradiated body. This PSD provides particle distributions in the PS plane, thus, in this sense, PSD files can be used directly as source models.3,4,21–23 It has been shown that by adjusting the parameters of the electron beam above the target, followed by the full transport of particles through the beam-generating devices to the PS plane, the dose calculation using that PSD file is able to accurately match the measured dose.9,15,20,23,24,31–33 However, the flexibility of directly using a PSD file is limited when adjusting the data for use with accelerators with slightly different outputs. The parameters of the initial electron beam are treated as adjustable parameters, since they are not known in advance. Hence, the beam characterization is done iteratively by adjusting the incident electron-beam parameters to best match calculated dose distributions with measurements. Thus, researchers from several institutions have conducted studies that result in different parameters for the initial electron beam hitting the target in order to match their own accelerators’ output.3,4,9,11,15,16,19–24 Applying this method in general requires local expertise in implementing the MC PSD simulation, including the imple-
mentation of an accurate geometric model of the local linear accelerator. Furthermore, each iteration—using different electron source parameters—is both labor intensive and time consuming. However, recently Kawrakow et al. demonstrated that fast treatment head simulations can be performed, which has the potential to speed up iterative commissioning in the future or to replace the need for source models altogether.

Apart from using analytical source models or the PSD file itself as a source model, another approach is to create a histogram-based source model from the PSD. For these source models, the PSD is divided in subsource PSDs, each representing a main component of the beam defining system within the accelerator head, such as the target, the primary collimator, or the flattening filter. By sampling the initial parameters of a particle from these histogram distributions, these source models reconstruct the photon beam at the PS plane. However, histogram source models suffer from the same disadvantages as full PSD models in terms of adjusting the model to match to a given user’s accelerator unless a method is developed to adjust the histogrammed subsources to match measurements. This requires knowledge of the sensitivity of the accelerator output when the initial electron source parameters change, i.e., to identify how each subsource needs to be changed and what the suitable ranges for these changes are. Adjustable histogram-based source models should allow matching to an individual user’s accelerator beams without having to reperform the entire MC simulation; only scaling of subsource histogram distributions from a standard precomputed MC simulation would be required to tune the source model to match a user’s beam. Therefore, our aim in this work is to investigate the sensitivity of the subsource characteristics as a function of initial electron parameters for 6- and 18-MV photon beams. For this purpose, PSD was calculated for a variety of parameter sets of the initial electron beam data, including the radiation transport of photons, electrons, and positrons (photoneutron and neutron interactions were ignored). The PSD was analyzed in terms of energy, fluence, and energy fluence distributions on a subsource-by-subsource basis at source-to-surface distances (SSDs) of 50, 100, and 200 cm. Hence, in this study we provide information about the extent and within what ranges each subsource is affected by changes of the initial electron-beam parameters.

II. METHODS AND MATERIALS

In this section, the creation of the PSD for the multiple parameter sets is described in detail followed by a description of the analysis of the PSD in terms of energy, fluence and energy fluence distributions.

A. Creation of phase-space data

MC simulations of the radiation transport for 6- and 18-MV photon modalities of a Varian Clinac 21EX (Varian Oncology Systems, Palo Alto, CA 94304) were performed using BEAMnrc. The treatment-head geometry and materials used as input were based on data supplied by the accelerator’s manufacturer and previous publications. Simulations were initiated with electrons perpendicularly striking the target. Primary and secondary particles including photons, electrons, and positrons were transported through the beam-defining system, which contains the target, primary collimator (PC), vacuum window, flattening filter (FF), monitor chamber, field light mirror, and intervening air below the vacuum window. Particles were transported to a plane directly above the secondary collimator jaws, where their coordinates were saved in a PSD file. Several studies have shown that the initial electron fluence above the linear accelerator target can be described by three parameters, namely, the mean electron energy \( E_e \), the electron energy spread \( \sigma_{E_e} \), typically assumed to be normally distributed, and the radial intensity spread \( \sigma_r \) of the electrons, also typically assumed to be normally distributed. The angular distribution of the electron beam incident on the target is ignored in this work, since Sheikh–Bagheri and Rogers concluded in their study that credible divergences of up to 0.5ª, show no observable effect on dose and in-air off axis factors. In this study, the three parameters, \( E_e, \sigma_{E_e}, \) and \( \sigma_r \), were used to define groups in which the parameter in question were modified while keeping the other parameters fixed. In group I, \( E_e \)

<table>
<thead>
<tr>
<th>Group</th>
<th>Mean energy: ( E_e ) in MeV</th>
<th>Energy spread: ( \sigma_{E_e} ) in % of ( E_e )</th>
<th>Radial intensity: ( \sigma_r ) in mm</th>
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<tr>
<td>I</td>
<td>5.0</td>
<td>1.28</td>
<td>0.96</td>
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<td><strong>0.96</strong></td>
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<tr>
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<tr>
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<tr>
<td>III</td>
<td>6.2</td>
<td>2.56</td>
<td>0.96</td>
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was varied, in group II, $\sigma_r$ was varied, and in group III, $\sigma_E$ was varied. Table I and Table II give an overview of the combinations for which PSD was computed for the 6- and 18-MV beams, respectively. An energy spread of $\sigma_E = 1.28\%$ corresponds with a full width half maximum (FWHM) of 3\%, and a radial intensity spread $\sigma_r$ of 0.96 mm corresponds with an FWHM of 2.27 mm. A standard parameter set (SPS) was defined for each beam energy, and for this set of parameters, previous dose calculations in water agreed to within 1\% or 1 mm with measurements in a water phantom. On the basis of these SPS, the mean energy was varied by about ±1 MeV, and the radial intensity as well as

<table>
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<tr>
<th>Group</th>
<th>Mean energy: $\bar{E}_e$ in MeV</th>
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<th>Radial intensity: $\sigma_r$ in mm</th>
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<td>III</td>
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Fig. 1. Energy spectra of the 6-MV beam for group I ($\bar{E}_e$). (a) Target subsourse. (b) Primary collimator subsourse. (c) Flattening filter subsourse. (d) Electron subsourse. Additionally, for better legibility, an error bar is only plotted at 0.9 MeV. The energy spectra are normalized so that the sum of all bin values is equal to one. The legend refers to the mean energy $\bar{E}_e$ of the initial electron beam in MeV.
The energy spread were varied by factors of 0, 0.5, and 2.0. These parameter ranges cover most of the parameter settings used for PSD calculations at several research institutions.\textsuperscript{5,8,9,11,14,15,17,19,21–24} In the remainder of this paper, each group is referred with the particular parameter changed shown in parentheses. For example, group I ($E_e$) refers to the parameter sets within group I, in which the mean energy of the initial electron beam $E_e$ was changed.

For all of the MC simulations, the threshold energies for electron and photon transport, $\text{ECUT}$ and $\text{PCUT}$, were set to 0.70 and 0.010 MeV, respectively, except in the target for the 18-MV beam, where the value of $\text{PCUT}$ was increased to 0.15 MeV, which had been previously shown to negligibly impact the PSD.\textsuperscript{17,24} The discrete electron and photon creation thresholds, $AE$ and $AP$, were set to 0.70 and 0.010 MeV, respectively. The default bremsstrahlung cross sections, i.e., Bethe-Heitler, were used for all MC simulations. To reduce the calculation time, the “uniform bremsstrahlung splitting” variance reduction technique was applied with a bremsstrahlung splitting number of 20. The splitting number was not applied to higher-order bremsstrahlung and annihilation photons. For the 6 and 18-MV beams, at least $100 \times 10^6$ and $20 \times 10^6$ histories, respectively, were simulated leading to at least $106 \times 10^6$ (6 MV) and $95 \times 10^6$ (18 MV) particles in the PSD files directly above the secondary collimator jaws.

The PSD file contains the following data for each particle crossing the PS-scoring plane at a given z coordinate:

$$P = [x, y, u, v, E, q, \text{weight}, \text{LATCH}],$$

where $x$ and $y$ are the position coordinates of the particle; $u$ and $v$ are the direction cosines in the $x$ and $y$ directions, respectively; $E$ is the energy; $q$ is the charge; weight is the particle statistical weight; and \text{LATCH} is a tag that records the history of the previous particle interaction locations. The total PSD was separated into PSD files for the target, PC and FF, based on the location of the last interaction of the photons. With these three subsourse PSDs, over 99.5% of all photons scored in the total PSD file were used. The remaining 0.5% of the photons had their last interaction in air or in one of the other head components (ionization chamber, mirror, etc.). As a result, they were excluded from this study. In addition, a PSD file for the contaminant electrons was separated from the total PSD.

### B. Analysis of subsourse phase-space characteristics

The phase-space analysis was limited to PSD particles that have the potential to contribute to the patient’s radiation dose for field sizes up to $42 \times 42$ cm$^2$ at the isocenter plane (the maximum field size achievable with this accelerator is $40 \times 40$ cm$^2$ at the isocenter plane). This was accomplished by determining the intersection of each particle’s trajectory with the isocenter plane (SSD 100 cm) for each particle from the subsourse PSD, presuming the material between the PSD plane and the isocenter plane was a vacuum, and by keeping all particles within a radius $\leq 30$ cm of the central axis at the isocenter plane. For an analysis of the directional distributions at SSDs of 50 and 200 cm, particles within 15 cm (SSD 50 cm) and 60 cm (SSD 200 cm) of the central axis were used.

Subsourse PSD data was analyzed in terms of fractional fluence and energy fluence components for each parameter set within a group. The fractional fluence and energy fluence components for the PC and FF were defined as ratios at the isocenter plane of the planar fluence and planar energy fluence contributions from the PC and FF subsourses to those for the target. The fractional components for the electron subsourse were determined as a ratio at the isocenter of the planar electron fluence and energy fluence to those from the three photon subsources together. For these ratios the fluence and energy fluence was determined over the full region, i.e., 30 cm diameter at the isocenter. In addition, the energy distributions for each subsourse and parameter set were determined, and, thereby, the energy spectra, averaged over the whole field, were established. Apart from these energy spectra, the mean energy as a function of the off-axis distance was evaluated. Furthermore, the beams were characterized in terms of radial fluence and radial energy fluence distributions for all parameter sets, each subsourse, and both beam energies. Within this analysis, the energy spectra, the radial mean energy, the radial fluence, and the radial energy fluence distributions were evaluated in the form of histograms. The number of bins depended on the subsourse and the considered quantity, whereas the bin widths changed with off-axis distance for the radial distributions to achieve similar statistical uncertainties in each bin. Changing the initial electron-beam parameters, especially $E_e$, affected the photon yield, and consequently the fluence and energy fluence distributions. Hence, to compare the shape of the radial energy fluence between parameter sets, the radial energy fluence was normalized to the integral value calculated for the SPS (integral normalization).

### III. RESULTS AND DISCUSSION

The results are structured in sections where each section contains the results of the parameter groups for one physical quantity.
A. Fractional fluence

The fractional fluence components for the parameter sets of group I ($E_e$) and group II ($\sigma_r$) are given in Table III and Table IV for the 6 and 18-MV beams, respectively. For the FF and PC subsources, the largest variations in the fractional fluence occurred in group II ($\sigma_r$) with $\sigma_r$ set to its extreme values. Compared with the SPS, the FF fractional fluence component changed from a decrease of 6% (6 MV) and 4% (18 MV) with $\sigma_r = 0$ to an increase of 3% (6 MV) and 4% (18 MV) with $\sigma_r$ at the maximum value tested. For the same case, the PC subsource showed a decrease of 19% (6 MV) and 10% (18 MV) and an increase of 24% (6 MV) and 14% (18 MV). This is due to the fact that as $\sigma_r$ increases, more particles from the target strike the PC due to the increased radial geometric proximity of the PC with respect to the photon source. This, in turn, produces increasing scatter for the PC subsource and decreases the fluence for the target subsource. Then, more particles strike the thinner part of the FF, and the scatter from the FF decreases. However, this decrease is less compared with the decrease of the target fluence. For group I ($E_e$) the geometry remains constant, leading to smaller changes in the relative fluences compared with those for group II ($\sigma_r$). The largest deviation for the electron subsource was observed for group I ($E_e$), with a decrease of $\sim 16\%$ (6 MV) and $\sim 4\%$ (18 MV) at the minimum $E_e$ of the group and an increase of $\sim 10\%$ (6 MV) and $\sim 5\%$ (18 MV) at the maximum $E_e$ of the group. This is because higher-energy photons produce higher-energy, more forward directed electrons. Overall, the fractional fluence variations were lower for the 18-MV beam compared with those of the 6-MV beam—within the range used in the parameters sets. The variation of the fractional fluence with $E_e$ and $\sigma_r$ indicates that the relative weights of the subsource change when the initial electron beam on the target changes (i.e., for different parameter sets) and, hence, needs to be taken into account when tuning the source model to match measurements. The effects on the fractional fluence components in group III ($\sigma_F$) was negligible, i.e., the results agree to within two standard deviations, hence, they were not listed in Table III and Table IV.

B. Fractional energy fluence

Table V and Table VI show the results for the fractional energy fluence for the 6 and 18-MV beams, respectively. Since the mean energy for the target subsource photons is higher than for the FF and PC subsource photons, their fractional energy fluence components are lower than their corresponding fractional fluence components. The fractional energy fluence for different parameter sets in group II ($\sigma_r$), compared with the SPS, shows the same trends as those for the fractional fluence: For increasing $\sigma_r$ in group II ($\sigma_r$), the fractional energy fluence for the FF subsource changed from a decrease of 6% (6 MV) and 4% (18 MV) with $\sigma_r = 0$ to an increase of 3% (6 MV) and 4% (18 MV) with $\sigma_r$ at the maximum value used. For the PC subsource, these values changed from a decrease of 17% (6 MV) and 10% (18 MV) to an increase of 22% (6 MV) and 16% (18 MV).

The group I ($E_e$) fractional energy fluence results, however, show opposite trends compared with those found for the fractional fluences. This is due to the fact that for increasing incident photon energy, the fraction of energy retained by the Compton photon decreases, on average. As $E_e$ increases, the ratio of the mean photon energies decreases more rapidly.
than the corresponding ratio of the photon fluences increase (see Table III and Table IV), causing the fractional energy fluences to decrease.

Again, the fractional energy fluence for the electrons changed most for group I \( E_e \) and resulted in deviations of up to 14%. The analysis showed virtually no changes, i.e., the results agree to within two standard deviations, for the fractional fluence and fractional energy fluence components for group III \( \sigma_{E_e} \); thus, they were not listed in Table V and Table VI.

C. Energy spectra and mean energy

Figure 1 illustrates the energy spectra for each subsource for the 6-MV beam of group I \( E_e \). These spectra show the largest changes in shape for all parameter groups investigated. The energy spectra are normalized so that the sum of all bin values is equal to one; thus, each bin value represents its probability. For increasing \( E_e \), photons with higher energy were produced and, consequently, the fraction of low-energy photons is reduced in the photon energy spectra, leading to an increase of the mean photon energy. This can also be seen by the mean energy as a function of off-axis distance in Fig. 2(a) and Fig. 2(b) for group I \( E_e \). The mean energy decreases about 20% and increases about 10% when an \( E_e \) of 5.0 or 7.0 MeV is used instead of 6.2 MeV in the SPS, respectively. The analogous results for the 18-MV beam are depicted in Fig. 2(c) and Fig. 2(d). The impact of the PC on the target subsource is clearly visible at off-axis distances greater than 25 cm, beyond which the beam is attenuated by the PC (see Fig. 4). However, whereas beam hardening appears for the 6-MV beam, beam softening due to the increased attenuation of high-energy photons in the PC occurred in the 18-MV beam. Note, for the electrons the mean of the total energy is depicted and does not include energy loss in air between the plane where the PSD was acquired and the isocenter. The changes of the energy distributions for group III \( \sigma_{E_e} \) were negligible. These results agree with those published by others.\(^{13,15,22}\) For example, for a 10 \( \times 10 \) cm\(^2\) field size, Ma \textit{et al.}\(^ {13} \) determined that the mean energy for the FF subsource is around 1.3 MeV for a Varian Clinac 2300C/D 6 MV photon beam. For a 40 \( \times 40 \) cm\(^2\) field size, Fix \textit{et al.}\(^ {15} \) obtained results similar to Fig. 2(b) for the FF and PC subsources. In this latter study, slightly higher and lower mean energies were reported for the target and electron subsource, respectively. However, the plane where the mean energy distributions were evaluated is not the isocenter plane as used in our present study, but rather a plane directly below
Fig. 3. Radial fluence distribution in the isocenter plane. (a) Target subsource of the 6-MV beam for group I ($E_0$). (b) The same as (a), but normalized to the same integral value of the standard parameter set (6.2_1.28_0.96). (c) The same as (a) for the 18-MV beam. (d) The same as (c), but normalized to the same integral value of the standard parameter set (18_1.28_0.64). Where no error bars are visible, the statistical uncertainties are smaller than the linewidth used for plotting. The legend refers to the mean energy $E_0$ of the initial electron beam in MeV.

Fig. 4. Radial fluence distribution in the isocenter plane. (a) Target subsource of the 6-MV beam for group II ($\sigma_r$). (b) The same as (a) for the 18-MV beam. Where no error bars are visible, the statistical uncertainties are smaller than the linewidth used for plotting. The legend refers to the radial electron intensity distribution $\sigma_r$ in mm.
the secondary collimator jaws. In the study by Sheikh-Bagheri et al., the mean energy distributions for the target subsource agree with the present study’s data for the 6- and 18-MV beams. The decreasing mean energy as the off-axis distance increases for the combined beam is in agreement with other studies. However, none of these previous studies show how the mean energy distribution is affected by changing the initial electron source nor show the data for the subsources.

D. Radial fluence distributions

Figure 3 shows the sensitivity of the target subsource fluence as a function of the off-axis distance at the isocenter plane for different parameter sets. The fluence increased significantly for group I ($E_e$), where the mean energy $E_e$ was increased [Fig. 3(a) and Fig. 3(c)]. This is due to the fact that the radiation yield increases and is more forward directed with increasing electron energy. As a consequence, the shapes of the radial fluence distributions for the target subsource change significantly with an increase of the central axis fluence relative to the off axis fluence, as shown in Fig. 3(b) and Fig. 3(d). In Fig. 4(a) and Fig. 4(b), the radial fluence distributions for group II ($\sigma_r$) are shown. The maximum fluence is shifted to larger off-axis distances for decreasing $\sigma_r$ of the initial electron beam. The deviation for the maximum fluence is up to about 20% compared with the SPS. These changes in the fluence distributions result from the effect that more bremsstrahlung photons are absorbed or scattered by the PC as $\sigma_r$ increases. The radial fluence distributions for the PC, the FF, and the electron subsource for group I ($E_e$) are illustrated in Fig. 5. The general behavior is the same as for the target subsource, i.e., increasing the mean initial electron energy $E_e$ results in increased radial fluence distributions. This is because the increased fluence from the target impinging on the FF and the PC result in increased scatter radiation from these subsources. However, whereas the shape of the radial fluence distribution changes significantly for the target subsource, Fig. 5(b) and Fig. 5(d) demonstrate that for nontarget subsources the distribution shapes remain the same. Note, in Fig. 5(b) and Fig. 5(d), the integral

Fig. 5. Radial fluence distribution in the isocenter plane for the primary collimator (PC), the flattening filter (FF), and the electron subsource for group I ($E_e$). (a) For the 6-MV beam. (b) The same as (a), but normalized to the same integral value of the standard parameter set ($E_e = 6.2, 1.28, 0.96$). (c) For the 18-MV beam. (d) The same as (c), but normalized to the same integral value as the one for the standard parameter set ($E_e = 18, 1.28, 0.64$). The numbers in the plot correspond with the according $E_e$ in MeV, where $E_e$ refers to the mean energy of the initial electron beam. Where no error bars are visible, the statistical uncertainties are smaller than the linewidth used for plotting.
normalization was applied. The normalized radial fluence distributions are within their statistical uncertainty, i.e., within about 1% (1 SD).

For the nontarget subsources, Fig. 6 illustrates the radial fluence distribution for group II ($\sigma_r$). The fluence distributions for this group compared with those for the SPS vary by 16% for 6 MV and 4% for 18 MV. The integral normalization of these distributions demonstrates that the shapes of the radial fluence distributions for each subsource remain within their statistical uncertainty of about 1%. This is an important result that will be discussed later in this paper.

The normalized data for the FF, PC, and electron subsources for group I ($\bar{E}_e$) and group II ($\sigma_r$), but evaluated at SSDs of 50 and 200 cm, shows that the deviation between the normalized fluence distributions is within 1.5% for all SSDs analyzed and both beam energies. Hence, this data suggests that while the target subsource characteristics are strongly sensitive to the parameter set used, the changes for the nontarget subsources could be described by changing the relative weight of the subsources relative to the target subsource.

E. Radial energy fluence distributions

Figure 7 shows the radial energy fluence as a function of the off-axis distance for the target subsource for group I ($\bar{E}_e$) and group II ($\sigma_r$). The energy fluence distributions change in values and shape due to the changes in the radial mean energy and fluence distributions. For the same two parameter groups, Fig. 8 illustrates the results for the nontarget subsources. The radial energy fluence increased with increasing $\bar{E}_e$ in group I ($\bar{E}_e$) for all subsources and both beam energies. For example, the energy fluence at the central axis increases by a factor of about 2.5 when $\bar{E}_e$ is increased from 5.0 to 7.0 MeV. The FF, PC, and electron subsources show less sensitivity in terms of the energy fluence distributions for the range of $\sigma_r$ used in this work [Fig. 8(b) and Fig. 8(d)]. The shapes of the radial energy fluence for all nontarget subsources were found to be virtually constant (within their statistical uncertainty of about 1.5%) after integral normalization was applied.

The results for the radial energy fluence distributions for the parameter sets within group III ($\sigma_E$), where the energy spread of the initial electron beam $\sigma_E$ was changed, show that the deviations of the energy fluence, compared with those for the SPSs for all subsources, were within the statistical uncertainties of about 1.5% (1 SD).

IV. SUMMARY AND CONCLUSIONS

In this work, the impact of the initial electron-beam parameters on the photon-beam subsource distributions was investigated. For this purpose, the initial electron beam impinging the target for 6- and 18-MV photon beams was described by the mean electron energy, the electron energy spread, and the radial intensity distribution of the electrons. Parameter sets were defined, changing one parameter at a time and grouped according to the parameter changed. For each parameter set, PSD was computed using full MC simulations of the radiation transport through the accelerator head and afterward separated into subsource PSDs. Subsource-by-subsource comparisons of the subsource characteristics were performed in terms of energy, radial mean energy, radial fluence, and radial energy fluence distributions for SSDs of 50, 100, and 200 cm. The parameter changes showed a larger influence on the 6-MV beam compared with the influence on the 18-MV beam for the range used within the parameter sets.

Changing the parameter $\bar{E}_e$ resulted in the largest changes for the energy distributions as well as for the values of the fluence and energy fluence distributions for both beam energies. Whereas varying the parameter $\sigma_r$ led to a significant change in the shape of the radial fluence and the radial energy fluence distributions of the target subsources for the 6- and 18-MV beams, at each SSD these distributions retained their shape for the FF, the PC, and the electron subsources. The deviations for all quantities used to characterize the pho-
ton beams, when the parameter $\sigma_E$ was changed, were within their statistical uncertainties, i.e., the subsource characteristics of the 6- and 18-MV beams were not sensitive on $\sigma_E$ for the range of $\sigma_E$ used. Since this study explicitly used the geometry and materials for a specific accelerator design (the Varian 21EX) at specific energies, the results are not necessarily generalizable to other beam energies or linear accelerator designs, although presumably with qualitatively comparable results, e.g., Sheigk-Bagheri and Rogers\textsuperscript{22} as well as Faddegon et al.\textsuperscript{35}.

The results of this study contain valuable information for the commissioning procedure of MC source models. The data obtained suggests that besides the target subsource, only the relative weight to the target subsource and the energy spectrum need to be changed for the other subsources in order to adjust the source model to match differently tuned accelerators. This has the potential to ease the MC source model commissioning procedure substantially. In addition, this study provides information about the range that sub-sources should be changed; for example, Fig. 1 shows the energy spectrum variations for each subsource when different mean energies for the initial electrons are used. For a histogram-based source model, the variation can be accounted for by scaling the energy histogram distributions that represent the subsource to be tuned. Furthermore, an iterative procedure similar to that described by Sheigk-Bagheri and Rogers\textsuperscript{23} to determine the optimal parameters for the initial electron beam could be applied to histogram-based source models such as that described in Fix et al.\textsuperscript{17} via the following:

(a) Starting with the source model for the SPS.
(b) Matching calculated and measured depth-dose curves; select an $E_E$ and modify the histograms affected by this parameter in the source model, i.e., scaling the subsource energy spectra according the data from Sec. III C while simultaneously adjusting the relative subsource intensity for the scattered sub-sources by interpolating the data from Sec. III A. Select a different $E_E$ until depth-dose curves match.

![Fig. 7. Radial energy fluence distribution in the isocenter plane.](image-url)
Matching calculated and measured in-air off-axis factors; select an $\sigma_r$ and modify the histograms affected by this parameter in the source model according to the change in $\sigma_r$ of group II (see Sec. III D), i.e., adjusting the histogram describing the radial fluence distribution of the target subsource while simultaneously adjusting the relative subsource intensity for the scattered subsources by interpolating the data from Sec. III A. Note that the scattered subsource histogram distributions could remain constant. Select a different $\sigma_r$ until in-air off-axis factors match.

Iterate the procedure (b) to (c) until the acceptance criteria are fulfilled.

The data presented in this study provides the basic information and the ranges within the source model histograms should be adjusted during the tuning process.

In this publication, only a subset of all analyzed data is presented, since there is a high volume of data for the energy spectra, mean energy, fluence, and energy fluence distributions. However, a full set of results is available from the authors upon request.

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