Source Model Tuning for a 6 MV Photon Beam used in Radiotherapy

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Abstract. The purpose of this work was to do a feasibility study on a procedure for tuning the mean energy \( E \) and the spatial spread \( \sigma_R \) of the initial electron beam hitting the bremsstrahlung target as a part of a multicomponent source model, so that dose distributions predicted by Monte Carlo simulations (MC) will dosimetrically match measurements. The dose in a water phantom is considered to be a sum of doses produced by different components of a linear accelerator, namely target (TGT), flattening filter (FF), and primary collimator (PC). A histogram-based source model is used to model the phase space output of the 6 MV linear accelerator (VARIAN CL21EX). The phantom dose contribution from the target subsource has the greatest sensitivity to the initial beam parameters \( E \) and \( \sigma_R \), whereas the FF and PC subsource dose distributions are only weakly dependent on them. In order to create a source model that could be tuned and used for a continuous range of \( E \) and \( \sigma_R \), a method to interpolate across the histograms created with this data and to determine the sampling weights is developed, i.e. energy and radial-dependent interpolative polynomial fits to the histograms. The simulated dose distribution is then iteratively tuned to measured dose by changing the beam parameters, computing the corresponding dose distribution and compare simulation with measurements. This process is repeated until simulated dose matches measurements. The method ensures that the relative weights of radiation subsources are consistent with those that would be derived from full MC simulations of the treatment head. For comparison, the depth dose and the lateral dose profiles at various depths of the 10 × 10 cm², 20 × 20 cm², and 30 × 30 cm² field sizes are used. This study showed that a general source model tuning is feasible.

1. Introduction

For a clinical use of Monte Carlo (MC) simulations the predicted dose must be within 2% or 2 mm of the corresponding measurement [1, 2]. The output of individual accelerators differs from one to another, even for accelerators of the same model and vendor. Since MC dose calculation requires modeling of the input source, accelerator-dependent adjustments need to be done for each individual accelerator. Adapting the MC source to match the output of different machines is currently an inefficient time-consuming process and requires MC expertise. Basically, MC for dose calculation in radiotherapy simulates electrons incident on the target and transports the resulting particles – primary and secondary photons as well as charged particles – through the part of the accelerator, which remains the same for all patients.

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the transport of a particle, the particle’s information is saved in a phase space (PS). This saving can be done either by writing the particles data into a file (called PS-file), or, in the case of histogram based source models\(^2\)[6, 7], by binning the PS in histograms (the total of histograms used to describe the PS is referred to as PS-model)\(^3\). The dose in a patient or phantom can be computed by reloading these particles from the PS-file as input particle for the MC transport that simulates the patient dependent part of the accelerator. In order to fully recompute the PS, different histograms are used. These histograms contain the information about the particles in the isocenter plane, their energy distribution and their origin in the accelerator head. For the dose in a patient or phantom, MC simulations transport the particles in the PS (PS-file or PS-model) through the lower (patient dependent) part of the accelerator and the patient or phantom.

Several studies [3]-[10] on photon-beams showed that the MC dose predictions depend mainly on the characteristics of the initial electron beam hitting the target. These studies conclude that changing the electron beam’s parameters – mean energy (\(\mathcal{E}\)) and spatial spread (\(\sigma_R\)) at full width at half maximum (FWHM) – allows the MC output, i.e. the dose in a patient or phantom, to be tuned. This means that the beam parameters are adapted until the calculated dose matches measurements. Using PS-files for the tuning procedure, the dose to measurement adaption means a full MC computation with the new input parameters (\(E, \sigma_R\)) which is time-consuming. Within the PS-model, the shape of the histograms with different beam parameters (\(\mathcal{E}, \sigma_R\)) changes continuously as a function of \(\mathcal{E}\) and \(\sigma_R\). This means that for some given histograms with different combinations of \(\mathcal{E}\) and \(\sigma_R\), new histograms can be created by interpolation. This is from special interest since PS for new beam parameters can be generated by-passing a time-consuming MC simulation. Hence, an iterative process, that is faster than a similar process using PS-files, can be constructed where the dose distribution for a parameter set (\(\mathcal{E}, \sigma_R\)) is generated, compared with measurements and restarted with another beam parameter set until the simulated dose distribution matches measurements. Since this is a feasibility study, the dose distributions were computed for 42 different combinations of the parameter set (\(\mathcal{E}, \sigma_R\)) generated with interpolation. The dose distributions were generated for the 6 MV Cl21EX accelerator (Varian Oncology Systems, Palo Alto, CA, USA).

2. Methods and Materials
This section gives a brief introduction of the basics of the source model (section 2.1) and explains the influence of the beam parameters \(\mathcal{E}\) and \(\sigma_R\) on the dose distribution (section 2.2). The procedure to tune the source model such that the predicted dose will match measurements is illustrated. Further, the weight of the different subsources within the source model as well as the histogram interpolation method is discussed in section 2.4.

2.1. Source model
Within the source model of Fix \textit{et al.} [6, 7] the total PS is separated into subsource PS’s corresponding to the components of the accelerator head where the particles had their last interaction. With \texttt{BEAMnrc} [8, 9] this separation can easily be done using the LATCH variable.

Table 1 shows that the main subsources of the head geometries are the target (TGT), primary collimator (PC), and flattening filter (FF) whereas the charged particles (\(e^-\) and \(e^+\)) and the other head geometries are low in weight. For simplicity the latter subsources are neglected and since this work is about photons, the PS’s of the charged particles are not binned into histograms. However, in order to better reproduce the dose in the build-up region, the electrons

\(^2\) In this study, the source model developed by Fix \textit{et al.} [6, 7] is used.

\(^3\) It is important to distinguish between the PS, which is the total of all particle information, and the two methods of saving this data (PS-file or PS-model).
Table 1. Relative contribution of subsource particles in the initial phase space using a mean energy of $E = 6.2 \, MeV$ with $2.27 \, mm$ spatial spread at FWHM ($\sigma_R$) for the initial beam passing the sampling plane at the isocenter within a circle of radius $R = 30 \, cm$ around the beam axis.

| Subsource                          | Fraction of subsource particles in the initial PS [%] |
|------------------------------------|-----------------------------------------------------|
| Target (TGT)                       | 87.7%                                               |
| Primary Collimator (PC)            | 4.1%                                                |
| Flattening Filter (FF)             | 7.7%                                                |
| Electrons                          | 0.5%                                                |
| Positrons                          | 0.02%                                               |
| Mirror, Ionization Chamber, etc.   | $\approx\, 2\%$                                    |

and positrons PS-files are included in the source model.

There are different types of histograms in order to preserve the main physical information. For the TGT, the most simple histogram is called RSAMPLE where the particles passing the sampling plane (isocenter plane) are binned according to the radial distance from the beam axis. A second histogram, RORIGIN, is used to preserve the spatial information about the particles origin in a plane through the target’s downstream surface (TGT plane). In this histogram the particles within each RSAMPLE bin are again binned into radial bins according to the radial distance from the beam axis in the TGT plane (examples shown in Fig. 1). A third (not shown) histogram is the ENERGY histogram which is similar to the RORIGIN histogram but instead of binning the location in the TGT plane, the particles are binned depending on their energy in the sampling plane. For more information about the structure and the histograms of the other components PC and FF it is referred to the paper of Fix et al. [6].

![Figure 1.](image)

**Figure 1.** a) Histogram in the sampling plane. The counts of particles within a circle of radius 30 cm are binned regarding their radial distance from the beam axis in the sampling plane. b) Particles binned according to the radial distance in the sampling plane and the target plane. With this histogram the direction of motion is sampled. The axis refer to the bin number and the scale to the counts within a bin.
2.2. Beam parameters $\overline{E}$ and $\sigma_R$

It has been previously shown [4, 5, 11, 12] that changing the parameters $\overline{E}$ and $\sigma_R$ of the initial electron beam, which produces the photon beam, allows the tuning of the output of the dose distribution in the patient or phantom to match measurements. These electrons exhibit a range of kinetic energies $\sigma_E$ around $\overline{E}$ and show a spatial spread $\sigma_R$. Previous studies [4, 5] showed that the variation of the energy spread can be neglected for 6 MV beams. In addition, Tanabe et al. [13] showed that the energy spread can be assumed to be Gaussian-shaped at 3% FWHM of the mean beam energy for the accelerator considered in this work. Hence, $\sigma_E$ was set to 3% of $\overline{E}$ in this work and remains the same for all simulations. The two remaining beam parameters, $\overline{E}$ and $\sigma_R$, influence the dose distribution $D$ and, hence, are used for adapting the MC dose to dosimetrically match measurements. Since the PS is separated into subsources PS’s, the dose $D$ in a patient or phantom is the sum of the dose produced by the individual subsources $D_{subsource}$. Given a PS-file the relative weight $w_{subsource}$ of each subsource is given by the number of particles in the subsource-PS intrinsically. For the PS-model, however, the weight for a specific subsource can be derived from the number of particles from the subsource that cross the sampling plane within a certain area ($N_{subsource}$) around the central axis and the total number of all particles crossing this area ($N_{total}$):

$$w_{subsource} = \frac{N_{subsource}}{N_{total}}. \quad (1)$$

These weights are also valid\(^4\) for the cumulative dose $D$ in the patient or phantom which results in the following equation:

$$D = \sum_{subsource} w_{subsource} \cdot D_{subsource}. \quad (2)$$

In general, variations in the initial electron beam parameters, $\overline{E}$ and $\sigma_R$, change the dose contribution of each subsource and thus the total dose distribution in the patient. Consequently, this will also affect the weights of the subsource and eq. 2 becomes

$$D(\overline{E}, \sigma_R) = \sum_{subsource} w_{subsource}(\overline{E}, \sigma_R) \cdot D_{subsource}(\overline{E}, \sigma_R). \quad (3)$$

In principal, the dose distribution for any parameter set $(\overline{E}, \sigma_R)$ can be computed using eq. 3. Using the PS-model offers the possibility to compute dose distributions for all kind of combinations of the subsources. This is from special interest since Fix et al. [3] showed that the variation in the mean electron beam energy $\overline{E}$ and spatial spread $\sigma_R$ mainly affects the TGT dose distribution. The effect on the relative dose distribution of the remaining subsources PC and FF and the charged particles ($e^−$ and $e^+$) is small and can be neglected. However, while the shape of the dose distribution remains constant, the weight, i.e. their contribution to the total dose, changes for different $\overline{E}$ and $\sigma_R$ settings. Thus, these dose distributions are calculated once using a standard parameter set $(\overline{E}^{std}, \sigma_R^{std})$ where their contribution to the total dose is determined using the actual parameter set $(\overline{E}, \sigma_R)$. This behavior leads to the final form of the dose distribution in a patient or phantom.

$$D_{total}(\overline{E}, \sigma_R) = w_{TGT}(\overline{E}, \sigma_R) \cdot D_{TGT}(\overline{E}, \sigma_R) + \sum_{k \in \{PC, FF, e^−, e^+\}} w_k(\overline{E}, \sigma_R) \cdot D_k(\overline{E}^{std}, \sigma_R^{std}) \quad (4)$$

Hence, given a PS-model for a parameter set $(\overline{E}, \sigma_R)$, the total dose in a patient or phantom for another parameter set $(\overline{E}', \sigma_R')$ can be computed if the TGT dose distribution and the

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\(^{4}\) Particles that pass the sampling plane with a radial distance larger than 30 \text{cm} are not taken into account since their contribution to patient or phantom dose is negligible.
subsource weights for \((\bar{E}, \sigma_R)\) are known. There is no need to compute the other subsource
dose distributions for \((\bar{E}, \sigma'_R)\).

2.3. Tuning procedure

![Flow diagram of the general PS-model tuning using histogram interpolation.](image)

Satisfying agreement of simulated dose and measurements occurs when the correct
combinations of \(\bar{E}\) and \(\sigma_R\) are used as input parameters for the MC simulations. In order to find
this combination, an offset parameter \((\bar{E}, \sigma_R)_{offset}\) set can be tuned until the simulated doses
match measurements. Depending on the initial parameter set used as offset for the tuning,
several iterations need to be computed. Since simulating a full PS with MC is very time-
consuming, this method is not usable in an adequate time frame.

Figure 2 gives a schematic overview of the general tuning procedure with the PS-model. First,
each parameter set \((\bar{E}, \sigma_R)_{input}\) listed in table 2 is used as input parameters for the MC
simulation. In a second step, all PS’s are separated into subsource PS’s and the subsources
PS’s of the TGT, FF, and PC are then binned into histograms (see section 2.1). For the tuning
procedure, the histograms and subsource weights of any parameter set \((\bar{E}, \sigma_R)\) within the limits
of \((\bar{E}, \sigma_R)_{input}\) are considered for the tuning procedure. Therefore, the TGT histograms and
the subsource weights are interpolated as functions of \(\bar{E}\) and \(\sigma_R\). After choosing a parameter
set \((\bar{E}, \sigma_R)\), the TGT histogram and all subsource weights for this set are generated and the
TGT dose distribution can be simulated using MC. For the other subsources, the histograms for
one combination of \((\bar{E}, \sigma_R)_{input}\) is sufficient and their dose distribution is simulated once. The
total dose for the chosen parameter set is given by eq. 4. The last step is to compare whether
the dose for \((\bar{E}, \sigma_R)\) matches measurements or not. If the agreement is not acceptable, another
parameter set is chosen and the corresponding TGT histogram and weights are again generated
with interpolation.

Since this is a feasibility study, the procedure was shortened: instead of computing the total dose
for the parameter set \((\bar{E}, \sigma_R)\) in each iteration, a number of parameter sets were computed and
each dose was compared with measurement. The parameter set which matched measurement
closest was declared as ideal input parameters for MC simulations. The set used for this feasibility study was a grid with beam energies 5.0, 5.4, 5.8, 6.2, 6.6, and 7.0 MeV with spatial spreads 1.2, 1.5, 1.8, 2.1, 2.4, 2.7, and 3.0 mm.

2.4. Subsource weight and TGT histogram interpolation

\[
P = w'_{TGT}(E, \sigma_R) + w'_{FF}(E, \sigma_R) + w'_{PC}(E, \sigma_R) + w'_{e^-}(E, \sigma_R) + w'_{e^+}(E, \sigma_R)
\]

\[
w_{TGT} = \frac{w'_{TGT}}{P}
\]

\[
w_{FF} = \frac{w'_{FF}}{P}
\]

\[
w_{PC} = \frac{w'_{PC}}{P}
\]

\[
w_{e^-} = \frac{w'_{e^-}}{P}
\]

\[
w_{e^+} = \frac{w'_{e^+}}{P}
\]

**Figure 3.** Flow diagram for the subsource weight interpolation. The phase space for a set of initial electron beam parameters \(E\) and \(\sigma_R\) is separated into five subsource phase spaces. The weight for a subsource is determined using eq. 1. All weights for one subsource are interpolated as a function of both parameters \(E\) and \(\sigma_R\). If the two fits for each subsource are known one can determine the subsource weight for any parameter set \((E, \sigma_R)\) within their range \([E_{\text{min}}, E_{\text{max}}]_{\text{input}}\) and \([\sigma_R^{\text{min}}, \sigma_R^{\text{max}}]_{\text{input}}\), respectively, by combining the two fits \(w_{\sigma_R}(E)\) and \(w_{E}(\sigma_R)\) to \(w'(E, \sigma_R)\). The sum of all sampling weights is normalized by using \(P\). (The same flow diagram applies also to the target histogram interpolation, where the weight is replaced with counts in a fixed target histogram bin.)

For the tuning procedure, the subsource weights and the TGT histograms have to be determined as functions of the beam parameters \(E\) and \(\sigma_R\). A schematic overview of the weight interpolation is given in Fig. 3. Since a subsource weight is a scalar, it can be regarded as a function of \((E, \sigma_R)\) and, hence, be interpolated. However, the TGT histograms are vectors and the interpolation used for the subsource weights is not directly applicable. Therefore, each bin of a TGT histogram is interpolated separately. This means, that for a fixed bin, all counts of
Table 2. Phase spaces computed for different initial electron beam parameter combinations \((E, \sigma_R)_{\text{input}}\). The beam with \(E^{ld} = 6.2\) MeV and \(\sigma_R^{ld} = 2.27\) mm is used as standard beam and is used for both interpolation toward \(\sigma_R\) and \(E\). The units of \(E\) and \(\sigma_R\) are \([\text{MeV}]\) and \([\text{mm}]\), respectively.

| \(\sigma_R\) | 5.0 | 5.5 | 5.9 | 6.2 | 6.5 | 6.8 | 7.0 |
|-------------|-----|-----|-----|-----|-----|-----|-----|
| 1.13        |     |     |     |     |     |     |     |
| 1.60        |     |     |     |     | \(\times\) |     |     |
| 1.90        |     | \(\times\) |     | \(\times\) | \(\times\) | \(\times\) | \(\times\) |
| 2.27        | \(\times\) | \(\times\) | \(\times\) | \(\times\) | \(\times\) | \(\times\) |     |
| 2.70        |     | \(\times\) |     |     |     |     |     |
| 3.40        |     |     |     |     | \(\times\) |     |     |
| 4.54        |     |     |     | \(\times\) |     |     |     |

The TGT histograms for different parameter sets are regarded as a scalar function of \(E\) and \(\sigma_R\). Hence, the interpolated counts in this fixed bin can be interpolated. Interpolating each bin of a histogram produces an interpolated histogram.

As it will be shown in section 3.1, the parameters \(E\) and \(\sigma_R\) are independent variables. Hence, the interpolation for both TGT histograms and subsource weights can be done for the two variables independently. The final value for the subsource weight or the histogram bin results then from a combination of the interpolations of the two independent variables \(E\) and \(\sigma_R\). The PS’s, i.e, their corresponding subsource weights and TGT histograms, listed in table 2 are used as input data to generate interpolated TGT histograms and subsource weights for all kinds of combinations of \(E\) and \(\sigma_R\) within the given limits \([E_{\text{min}}, E_{\text{max}}]_{\text{input}}\) and \([\sigma_R^{\text{min}}, \sigma_R^{\text{max}}]_{\text{input}}\), respectively, of the parameter sets \((E, \sigma_R)_{\text{input}}\). In this work, the subsource weights and TGT histograms were interpolated with the interpolation TOOLBOX in MATLAB using polynomial fits with \(n \leq 3\) and \(n \leq 2\), respectively.

Since each bin of the TGT histograms is interpolated separately, the interpolation was checked to determine whether it generates histograms which would also be directly derived from the PS-model. For this purpose, a comparison was performed between histograms which either were generated directly from the PS for a parameter set that is not already a member of \((E, \sigma_R)_{\text{input}}\) or were the result of the interpolation procedure. An example of this comparison is shown in section 3.3 for the RSAMPLE histogram.

2.5. Comparison with measurements

For this study, the data set provided by the accelerator’s manufacturer (Varian Oncology Systems, *Clinac EX Precommissioning Data Package*), which agrees with the data measured at Virginia Commonwealth University (VCU) within measurement uncertainties, is used as measurement data. The spatial resolution of these measurements is 2 mm.

The PS’s used as input for the tuning procedure were computed with \textsc{beamnrc}[8]. Calculated and measured dose profiles for field sizes \(10 \times 10, 20 \times 20, \) and \(30 \times 30\) cm\(^2\) at water depths of 1.6, 5, 10, 20, and 30 cm were used for the comparisons. The SSD was set to 100 cm. The dose was computed with \textsc{vmc}++ [14, 17] for a \(60 \times 60 \times 40\) cm\(^3\) water phantom where 40 cm corresponds to the depth. The statistical uncertainty of the MC calculated dose distribution was about 0.5% for all voxels with dose \(D > 0.5 \cdot D_{\text{max}}\).

The following criteria have been used to determine the optimal parameter set \((E_c, \sigma_R)\) in this
feasibility study:

1. If the calculated depth dose values excluding the build-up zone have less than 100\% of their voxels within 1\% of the measured dose, the corresponding parameter set was rejected.

2. If the calculated dose profiles for the 10 \times 10 and the 20 \times 20 cm^2 fields have less than 100\% and 98\%, respectively, of the voxels agree within 2\% or 2 mm to measured dose for all profile depths, the corresponding parameter set was rejected.

Another indicator for agreement is the mean square error (MSE) between the calculated and measured dose. Profiles that match measurements close have a little MSE. Since the simulation should not only reproduce one profile, all profiles of all field sizes are taken into account. This is represented by the sum of all MSE’s of all profiles of all field sizes (given in eq. 5). Hence, the parameter set with the smallest sum of MSE \((S_{\text{min}} = \text{min}(S))\) is a candidate for the best fit. Since the MSE has statistical uncertainties, other parameter sets that have \(S\) within the statistical uncertainty \(\Delta(S_{\text{min}})\) of \(S_{\text{min}}\) are also considered to be possible candidates.

\[
S(\mathcal{E}, \sigma_R) = \sum_{k \in \text{Field size}} \left( \sum_{l \in \text{Profile depth}} MSE_{k,l}(\mathcal{E}, \sigma_R) \right)
\]

The final parameter set from the remaining candidates is determined by comparing the dose distributions for the largest field size which is 30 \times 30 cm^2 in this study. The parameter set \((\mathcal{E}, \sigma_R)\) with the highest percentage of voxels agreeing within 2\% or 2 mm to measured dose values is considered to be the closest fit to measurements and should be taken as input parameters for the initial electron beam.

3. Results

3.1. Independence of \(\mathcal{E}\) and \(\sigma_R\)

![Figure 4](image_url)

**Figure 4.** The subsource weight for the subsources target (a) and flattening filter (b) as function of the spatial spread \(\sigma_R\) for different beam energies. The figures show that the slope for all weights are the same, i.e. the change in relative subsource weights for different \(\sigma_R\) does not depend on \(\mathcal{E}\).

In order to determine whether or not \(\mathcal{E}\) and \(\sigma_R\) are independent, the subsource weights have been investigated as functions of \(\mathcal{E}\) and \(\sigma_R\), respectively. Fig. 4 demonstrates the results for the TGT subsource (Fig. 4a) and the FF subsource (Fig. 4b). Since the slope of these functions...
are the same for different electron beam energies, meaning that the difference between two subsource weights for two spatial spreads $\sigma_R$ does not depend on the electron beam energy $E$, it is concluded that the two parameters are independent. Although not shown, the same behavior is also seen with the other subsource weights and histograms.

3.2. Weight interpolation

In order to determine the subsource weight for a parameter set $(E, \sigma_R)$, the weight for the parameter set $(\bar{E}, \sigma_R^{\text{std}} = 2.27 \text{ mm})$ is calculated. This is done by polynomial fits of order $\leq 3$. In a second step the weight for the parameter set $(\bar{E}^{\text{std}} = 6.2 \text{ MeV}, \sigma_R)$ is determined by polynomial fits of order $\leq 2$. The interpolation fits for all subsources considered have a correlation higher than 0.999, except for the $e^+$ subsource, where the linear fit regarding $\sigma_R$ results in a correlation of 0.80. However, these subsource weights are very low and have a high statistical uncertainty, hence, their dependence on $\sigma_R$ is neglected. The fit functions for the TGT, FF, and PC subsources are shown in Fig. 5. The two step interpolation to determine the subsource weight for a parameter set $(\bar{E}, \sigma_R)$ is combined resulting in the following equations:

\begin{equation}
 w_{\text{TGT}}(E, \sigma_R) = 88.11 + 0.55 \times E - 0.07 \times E^2 + 0.52 \times \sigma_R
\end{equation}

\begin{equation}
 w_{\text{FF}}(E, \sigma_R) = 12.73 - 0.94 \times E - 0.20 \times E^2 - 0.02 \times E^3 + 0.25 \times \sigma_R - 0.02 \times \sigma_R^2
\end{equation}

\begin{equation}
 w_{\text{PC}}(E, \sigma_R) = 2.45 + 0.12 \times E + 0.40 \times \sigma_R
\end{equation}

\begin{equation}
 w_{e^-}(E, \sigma_R) = 0.11 + 0.06 \times E + 0.48 \times \sigma_R
\end{equation}

\begin{equation}
 w_{e^+}(E, \sigma_R) = -0.033 + 0.008 \times E
\end{equation}

3.3. Histogram interpolation

Figure 6 shows the comparison of two RSAMPLE histograms for the TGT subsourse using the parameter set $(E = 6.0 \text{ MeV}, \sigma_R = 1.80 \text{ mm})$ as input parameters. One is the RSAMPLE histogram from the PS-model and the other is generated with the histogram interpolation. Since the parameter set $(E = 6.0 \text{ MeV}, \sigma_R = 1.80 \text{ mm})$ is not used as input parameter set $(\bar{E}, \sigma_R)^{\text{input}}$ for the interpolation, the comparison shows the capability of the interpolation method. The relative local differences between the histogram bins are lower than 1.5%, except for bins with low counts. For the other histogram types, namely RORIGIN and ENERGY, the relative local difference is lower than 5%, but is higher in bins with low counts.

3.4. Comparison with measurement

The acceptance criteria for $(E, \sigma_R)$ as given in section 2.5 leads to the remaining parameter sets listed in table 3. Among these parameter sets $(E, \sigma_R)$, the parameter set with the smallest $S$ (see eq. 5) and those that are within its statistical uncertainty are listed in table 4. Taken into account the result of all comparisons, the final parameter set within this feasibility study is $(E = 6.2 \text{ MeV}, \sigma_R = 1.80 \text{ mm})$. For matching the Varian measurements, this parameter set is taken as best input parameters for MC. In this study, it was also shown that the sensitivity of the electron beam parameters on total dose is large for profiles at shallow water depths of large field sizes, i.e. although the beam parameter sets in table 4 generate the dose distributions that match measurements the closest, the profiles of these field sizes do not match measurements with 2% or 2 mm. Changes in the beam parameters $(E, \sigma_R)$ can be detected best for these profiles and future studies on beam parameter tuning should focus on these fields.
Table 3. Parameter sets ($E, \sigma_R$) resulting in the most voxels agreeing with the measured dose. These beams are possible candidates for the best fit for the measured data. The third column lists the sum $S$ of all mean square error of all profiles for all field sizes for one beam, as it is given in eq. 5.

| $E$ [MeV] | $\sigma_R$ [mm] | $S \pm \Delta S$ [$cGy^2/MU^2$] |
|-----------|-----------------|----------------------------------|
| 5.0       | 1.50            | $(8.98 \pm 0.54) \cdot 10^{-4}$  |
| 5.4       | 1.80            | $(8.23 \pm 0.51) \cdot 10^{-4}$  |
| 6.2       | 1.50            | $(11.20 \pm 0.67) \cdot 10^{-4}$ |
| 6.2       | 1.80            | $(8.63 \pm 0.53) \cdot 10^{-4}$  |
| 6.2       | 2.10            | $(8.57 \pm 0.53) \cdot 10^{-4}$  |
| 6.6       | 1.50            | $(9.58 \pm 0.57) \cdot 10^{-4}$  |
| 6.6       | 2.40            | $(10.39 \pm 0.60) \cdot 10^{-4}$ |

Table 4. Percentage of voxels agreeing within 2% or 2 mm to measured dose for the $30 \times 30$ cm$^2$ field size. The dose distribution computed with the input parameters $E = 6.2$ MeV and $\sigma_R = 1.80$ mm shows the most voxels within 2% or 2 mm. The largest differences between the beams can be seen in low depths.

| $E$ [MeV] | $\sigma_R$ [mm] | 1.6 cm | 5.0 cm | 10.0 cm | 20.0 cm | 30.0 cm |
|-----------|-----------------|--------|--------|--------|--------|--------|
| 5.4       | 1.80            | 94.0%  | 95.7%  | 100.0% | 99.2%  | 98.3%  |
| **6.2**   | **1.80**        | **96.6%** | **97.4%** | **100.0%** | **100.0%** | **99.2%** |
| 6.2       | 2.10            | 94.9%  | 96.6%  | 99.2%  | 99.2%  | 99.2%  |

4. Discussion and Conclusion

The purpose of this work was to study the feasibility of an interpolation procedure for tuning the source model, so that the MC-calculated outputs match measurement depth dose excluding the build-up region within 1% or 1 mm and profiles within 2% or 2 mm with respect to the dose maximum. This work demonstrates that it is possible to tune a source model in a general way and achieve reliable results, in which predicted outputs agree with measured data. For this purpose, the initial electron beam incident on the target for a 6 MV photon beam is studied, and subsource weights and target histograms of a previously developed source model are interpolated. The key parameters for this tuning process are the mean energy $E$ and radial intensity distribution $\sigma_R$ of the initial electron beam incident on the target. In order to tune these parameters such that simulated dose matches measurements, an accurate tuning procedure has to be able to generate dose distributions for any combination of these parameters $E$ and $\sigma_R$. Since this was a feasibility study, however, dose distributions were only computed for 42 combinations of $E$ and $\sigma_R$. From this set of parameter combinations, the parameter values having the closest agreement with the measured data are 6.2 MeV for the mean energy and 1.80 mm for the spatial spread of the initial electron beam.

It is shown that dose profiles for the $30 \times 30$ cm$^2$ at shallow depths are the most sensitive profiles for the field sizes investigated in this study. Further tuning methods should focus on these or larger field sizes, especially at shallow depths around the dose maximum. Since the proposed interpolation method dose not use any attribute specific to a 6 MV photon beam, it is assumed that the procedure can be applied to other beam energies as well. However, for high energy beams of other vendors, like 18 MV for Siemens, the influence of different energy...
distributions and spreads for the initial electron beam should be studied[22]. The areas for further investigation are as follows: the effect of changing $E$ and $\sigma_R$ may not be unique; different combinations of the two parameter settings may result in similar dose distributions. Hence, this degeneracy needs to be further investigated and characterized.
Figure 5. Subsource weights interpolated toward mean beam energy $\overline{E}$ (a-c) and $\sigma_R$ (d-f) for the three main subsources target (TGT), flattening filter (FF), and primary collimator (PC). The correlations for all fits are higher than 0.999. The variables $w^\sigma_R(\overline{E})$ and $w^E(\sigma_R)$ in the equations above the plots refer to the one dimensional interpolation, i.e the weight is interpolated as a function of $\overline{E}$ for a standard $\sigma_R = 2.27$ mm and as a function of $\sigma_R$ for the standard $\overline{E} = 6.2$ MeV, respectively.
Figure 6. Comparison of an interpolated RSAMPLE histogram with a histogram directly created from a target phase space with the beam parameter set ($E = 6.0 \text{ MeV}, \sigma_R = 1.80 \text{ mm}$) which was not used as input for the interpolation procedure. For large radial distances, the relative error becomes large which is due to the low counts in these bins.

Figure 7. Measured (–) and calculated (·) depth dose for a field size of $10 \times 10 \text{ cm}^2$ together with the relative difference $\Delta D = \frac{D_{\text{meas}}(r_i) - D_{\text{simul}}(r_i)}{D_{\text{meas}}}$, where $D_{\text{meas}}$ is the measured dose and $D_{\text{simul}}$ is the calculated dose. The calculation used the input parameter set $E = 6.2 \text{ MeV}$ and $\sigma_R = 1.80 \text{ mm}$. 
Figure 8. a,b) measured (–) and calculated (·) dose profiles for the field sizes 10 × 10, 20 × 20, and 30 × 30 cm² at water depths of 1.6 and 30 cm, respectively. c,d) The relative difference
\( \Delta D = \frac{D_{\text{meas}}(r_i) - D_{\text{simul}}(r_i)}{D_{\text{meas}}(r_i)} \) at off-axis distance \( r_i \) of the profiles in a,b), respectively.
References
[1] ICRU-24, “Determination of absorbed dose in a patient by beams of X or gamma rays in radiotherapy procedures,” International Commission on Radiation Units and Measurements, 1976, p.24
[2] ICRU-44, “Tissue substitutes in radiation dosimetry and measurement,” International Commission on Radiation Units and Measurements, 1988, p.24
[3] M. K. Fix, P. J. Keall, and J. V. Siebers, “Dosimetric impact of scattered photon subsources within a Monte Carlo photon beam Source Model for different initial mean electron energies,” American Nuclear Society topical meeting in Monte Carlo, Chattanooga, TN, 2005
[4] M. K. Fix, P. J. Keall, and J. V. Siebers, “Photon-beam subsource sensitivity to the initial electron-beam parameters,” Med. Phys. 32, 1164-1175 (2005)
[5] D. Sheikh-Bagheri and D. W. Rogers, “Sensitivity of megavoltage photon beam Monte Carlo simulations to electron beam and other parameters,” Med. Phys. 29, 379-390 (2002)
[6] M. K. Fix, P. K. Keall, and J. V. Siebers, “Monte Carlo Source Model for photon beam radiotherapy: photon source characteristics,” Med. Phys. 21, 3106-3121 (2004)
[7] M. K. Fix, M. Stampanoni, P. Manser, E. J. Born, R. Mini, and P. Ruegsegger, “A multiple Source Model for 6 MV photon beam dose calculations using Monte Carlo,” Phys. Med. Biol. 46, 1407-1427 (2001)
[8] D. W. Rogers, B. A. Faddegon, G. X. Ding, C. M. Ma, J. We, and T. R. Mackie, “BEAM: a Monte Carlo code to simulate radiotherapy treatment units,” Med. Phys. 22, 503-524 (1995)
[9] D. W. O. Rogers, B. Walters, and I. Kawrakow, BEAMnrc Users Manual, last edited 2005/01/06
[10] B. A. Faddegon, P. O’Brien, and D. L. Mason, “The flatness of Siemens linear accelerator x-ray fields,” Med. Phys. 26, 220-228 (1999)
[11] G. X. Ding, “Energy spectra, angular spread, fluence profiles and dose distributions of 6 and 18 MV photon beams: Results of Monte Carlo simulations for a Varian 2100EX accelerator,” Phys. Med. Biol. 47, 1025-1046 (2002)
[12] D. Sheikh-Bagheri and D. W. Rogers, “Monte Carlo calculation of nine megavoltage photon beam spectra using the BEAM code,” Med. Phys. 29, 391-402 (2002)
[13] E. Tanabe and R. W. Hamm, “Compact multi-energy electron linear accelerators,” Nucl. Instrum. Meth. Phys. Res. B. 10, 871-876 (1985)
[14] I. Kawrakow and M. Fippel, “VMC++, a Fast MC Algorithm for Radiation Treatment planning,” in XIII International Conference on the Use of Computers in Radiation Therapy (ICCR), ed W. Schlegel and T. Bortfeld, p.126-128, Springer-Verlag, Heidelberg, Germany, 2000
[15] M. K. Fix, H. Keller, P. Ruegsegger, and E. J. Born, “Simple beam models for Monte Carlo photon beam dose calculations in radiotherapy,” Med. Phys. 27, 2739-2747 (2000)
[16] J. V. Siebers, P. J. Keall, B. Libby, and R. Mohan, “Comparison of EGS4 and MCNP4b Monte Carlo codes for generation of photon phase space distributions for a Varian 2100C,” Phys. Med. Biol. 44, 3009-3026 (1999)
[17] I. Kawrakow, M. Fippel, and K. Friedrich, “3D electron dose calculation using a Voxel based Monte Carlo algorithm (VMC),” Med. Phys. 23, 445-457 (1996)
[18] A. E. Schach von Wittnau, L. J. Cox, P. M. Bergstrom, Jr, W. P. Chandler, C. L. Hartmann Siantar, and R. Mohan, “Correlated histogram representation of Monte Carlo derived medical accelerator photon-output phase space,” Med. Phys. 26, 1196-2110 (1999)
[19] I. Kawrakow, D. W. Rogers, and B. R Walters, “Large efficiency improvement in BEAMnrc using directional bremsstrahlung splitting,” Med. Phys. 32, 2883-2898 (2004)
[20] J. Van Dyk, R. B. Barnett, J. E. Cygler, and P. C. Shragge, “Commissioning and quality assurance of treatment planning computers,” Int. J. Radi. Oncol. Biol. Phys. 26, 261-273 (1993)
[21] P. J. Keall, J. V. Siebers, B. Libby, and R. Mohan, “Determining the incident electron fluence for Monte Carlo-based photon treatment planning using a standard measured data set,” Med. Phys. 30, 574-582 (2003)
[22] F. Verhaegen and J. Steinijens, “Monte Carlo modelling of external radiotherapy photon beams,” Phys. Med. Biol. 48, R107 - R164 (2003)