Efficient photon treatment planning by the use of Swiss Monte Carlo Plan

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Abstract. Currently photon Monte Carlo treatment planning (MCTP) for a patient stored in the patient database of a treatment planning system (TPS) usually can only be performed using a cumbersome multi-step procedure where many user interactions are needed. Automation is needed for usage in clinical routine. In addition, because of the long computing time in MCTP, optimization of the MC calculations is essential. For these purposes a new GUI-based photon MC environment has been developed resulting in a very flexible framework, namely the Swiss Monte Carlo Plan (SMCP). Appropriate MC transport methods are assigned to different geometric regions by still benefiting from the features included in the TPS. In order to provide a flexible MC environment the MC particle transport has been divided into different parts: source, beam modifiers, and patient. The source part includes: Phase space-source, source models, and full MC transport through the treatment head. The beam modifier part consists of one module for each beam modifier. To simulate the radiation transport through each individual beam modifier, one out of three full MC transport codes can be selected independently. Additionally, for each beam modifier a simple or an exact geometry can be chosen. Thereby, different complexity levels of radiation transport are applied during the simulation. For the patient dose calculation two different MC codes are available. A special plug-in in Eclipse providing all necessary information by means of Dicom streams was used to start the developed MC GUI. The implementation of this framework separates the MC transport from the geometry and the modules pass the particles in memory, hence no files are used as interface. The implementation is realized for 6 and 15 MV beams of a Varian Clinac 2300 C/D. Several applications demonstrate the usefulness of the framework. Apart from applications dealing with the beam modifiers, three patient cases are shown. Thereby, comparisons between MC calculated dose distributions and those calculated by a pencil beam or the AAA algorithm. Interfacing this flexible and efficient MC environment with Eclipse allows a widespread use for all kinds of investigations from timing and benchmarking studies to clinical patient studies. Additionally, it is possible to add modules keeping the system highly flexible and efficient.

1. Introduction
Currently most commercial treatment planning systems (TPSs) offer neither an efficient interface to external dose calculation engines nor photon Monte Carlo (MC) treatment planning. Typically, a cumbersome multi-step procedure including many user interactions is needed to perform an external MC dose calculation for a given patient treatment plan. This means that the treatment plan must be exported, several programs or scripts are needed to provide the appropriate input files which might be
located in dedicated folders, and then the MC based dose calculation is started. Furthermore, to display and evaluate the resulting dose distribution either external viewing and analysis tools have to be available or the dose distribution must be imported in the TPS. If this procedure is to be performed routinely, it is difficult to keep track on all the files and data which will be accumulated. Consequently, automation of such a procedure is needed for usage in clinical routine.

In research institutions, the MC method is widely used for modeling linear accelerators in medical physics as well as for dose calculations [1-10]. The MC technique is known to produce accurate patient dose distributions, especially in regions of tissue inhomogeneities such as lung [11] and for surface irregularities. A major disadvantage for photon beams is the long computing time needed to get reasonable statistical accuracy in the calculated dose distributions. Hence, optimization of the MC calculations is essential. Usually, the MC particle transport is divided into three different parts: a source part, a beam modifier part and a patient part. The first part deals with the patient independent components of the linear accelerator, whereas the second part handles all beam modifications before the patient. Finally, the patient part copes with the MC dose calculation. This division is also realized in the photon MC treatment planning environment called Swiss Monte Carlo Plan (SMCP) [12-14]. Such a structure provides a flexible research framework needed to investigate appropriate MC transport methods to different geometric regions, i.e. the geometry and the MC transport is separated.

In this work we describe a framework which interfaces the Eclipse TPS (Varian Medical Systems, Palo Alto, CA) with the SMCP by means of a new GUI-based photon MC environment. This environment realizes the automation needed for routine treatment planning as well as the flexible framework needed for optimizing the MC transport in different geometric regions.

2. Materials and Methods

The schematic flow of the flexible and efficient framework for photon MC treatment planning is shown in figure 1. A research server client/installation of Eclipse within Aria (Version 7.5.42) was used to set up the treatment plans. Intensity modulated treatment plans were created using the Eclipse inverse treatment planning module HELIOS. By this means the user benefits from all available features of the TPS during the preparation of the treatment plan.

Figure 1. Schematic flow of the Swiss Monte Carlo Plan framework. See text for detailed description of the process.

A special plug-in within Eclipse, called Research API, was used to start the MC GUI. This plug-in provides all necessary information about both patient and beam data by means of Dicom streams. The
communication between the Eclipse Client and the Research API uses Remote Procedure Calls [15].

The SMCP framework reads these Dicom streams in order to calculate the dose distribution as described in more detail in the following sections. The calculated patient dose distribution is automatically transferred back into Eclipse. Hence, all display and evaluation tools of the TPS are available to inspect the dose distribution. Furthermore, the treatment plan and especially the dose distribution can be saved in the patient database and thus is included in the routine backup procedure.

The Research API and the SMCP framework are written in C++. Currently, 6 and 15 MV beams of a Varian 2300 Clinac C/D are available which is equipped with the 80 leaves MLC. In the following section the different parts of the framework are described in more detail.

2.1. MC GUI

After the Research API has been started, the framework reads the Dicom streams and starts the MC GUI. For the MC GUI implementation Qt (Version 4.1.0, Trolltech ASA, Oslo, Norway) was used which is a cross-platform application development toolkit using standard C++. Since the framework is used by different Eclipse Clients on different Windows Computers, the MC GUI and the framework communicate via the Common Object Request Broker Architecture (CORBA) [16]. CORBA is a standard defined by the Object Management Group that enables software components written in multiple computer languages and running on multiple computers to interoperate. The MC GUI allows the setting of the parameters for the MC calculation which are described in the following sections.

2.1.1. General settings. Within the general settings the patient name is shown as received by the Dicom stream from Eclipse and some general input information for SMCP is defined. Apart from settings for configuration folders and computers (nodes) or clusters where the MC calculation will be performed, a desired MC uncertainty for the dose calculation per field can be chosen. Thereby the MC uncertainty is the average in % of the statistical uncertainties (added in quadrature) of all dose values in the dose distribution with more than 50% of its maximum dose. Additionally, a configuration name must be defined which is used for the documentation of all settings selected in the MC GUI used for the current MC calculation.

2.1.2. Field settings. This section contains the field settings for which the dose calculation should be done. The field calculation mode is either set in the way that each computer node calculates one field or that the calculations for each field are distributed on all nodes. The SMCP framework allows two stop criteria for the MC simulations: the number of particles striking the patient or the number of primary electrons impinging on the linear accelerator target.

2.1.3. Source setting. Several sources are available one of which has to be selected in the MC GUI for each MC dose calculation. Phase space sources for the different photon beams have been pre-computed using the BEAMnrc package [17]. The treatment head materials and geometry information needed as input were based on data supplied by the accelerator’s manufacturer. The mean energy and the radial intensity spread of the initial electron beam have been selected to match measured dose distributions [7, 8]. The plane where the phase space files have been scored is directly above the secondary collimator jaws perpendicular to the beam central axis. Additionally, a pre-patient phase space file can be selected, i.e. in a first step the source and the beam modifier settings were used to generate a pre-patient phase space (see section 2.1.5) which then can be selected in a second step as a source for the dose calculation. This is useful for dose calculations where no changes in the beam system occur, as for example running different CT conversion schemas.

Apart from phase space files, histogram based source models created from phase space data are available. For the source models, the phase space data is divided into subsources, each representing a main component of the accelerator head and characterized by a set of histogram distributions [4, 9]. Sampling the particle’s initial parameters from these histograms allows the reproduction of the radiation beam in the initial phase space scoring plane. One of the implemented source models
includes already the secondary collimator jaws whereas the other reproduces the radiation beam above
the secondary collimator.

Further source options are full MC transport through the treatment head and the AAA beam model.
Full MC transport is done using VMC++ including the directional bremsstrahlung splitting [18].
Again there is the possibility to either include or exclude the secondary jaws. The AAA beam model
is used by the AAA algorithm [19] in Eclipse; it has been modified so that it can be used for MC
simulations and allows the investigation of its characteristics.

The MC calculation computes the dose in units of Gray per incident electron upon the target. Since
measured dose distributions are given in Gray per monitor unit and in order to calculate monitor units,
the MC calculated dose is normalized to measured data by determining the calibration factor for a
10×10 cm² depth dose curve [2]. The calibration factor is the constant that makes the area under the
MC calculated depth dose curve from 5 to 15 cm equal to that of the measured data. For the
correction of the backscatter into the monitor chamber the method developed by Liu et al. [20] has
been implemented.

The jaw transport section within the source settings is used for those sources including the
secondary collimator jaws.

2.1.4. Beam modifier. The beam modifier part consists of the modules jaws, enhanced dynamic
 wedge, multi leaf collimator (MLC), compensator, upper wedge, block and lower wedge. The
 implementation of this framework has been realized by separating the transport technique from the
 geometry, i.e. for each modifier its geometry and transport algorithm can be selected independently.
 The modules are connected through interface classes, hence the particles are passed in memory and no
 files are used for interfacing; nevertheless the option of writing phase space files as output exists. For
each of these modules two geometry settings are available: First, the exact geometry, in which the 3D
shape and material of the according beam modifier is implemented based either on the data supplied
by the manufacturer or on measured data. Secondly, a simplified geometry called flat geometry, in
which only the 2D area covered by the beam modifier in the mid-plane of the beam modifier
(perpendicular to the beam central axis) is used to determine whether a particle hits or misses the beam
modifier.

The available transport techniques depend on the geometry setting chosen. For the exact geometry,
one out of three full MC transport codes can be selected: EGSnrc, VMC++ or Photon Interaction
(PIN). The latter is an in-house developed MC code: The photon transport includes pair production,
Compton interaction, and photoelectrical interaction and the transport of charged particles is
simplified [21]; however, bremsstrahlung production is implemented.

Additionally, different complexity levels of the radiation transport can be applied during the
simulation: consider the beam modifier as totally absorbing (not for wedges and compensator),
consider attenuation only, consider first order Compton scatter or consider all Compton scatter. If on
the other hand side the flat geometry is used, only one of the two radiation transport codes is available:
totally absorbing (not for wedges and compensator) and attenuation only. For the totally absorbing
transport this means that the particle transport is stopped when the particle crosses the 2D area in the
mid-plane of the beam modifier. If the attenuation only transport is used, those particles’ weight will
be modified by the factor \( \exp(-\mu d) \), with \( \mu \) being the attenuation coefficient for the material of the
beam modifier at the particle’s energy and \( d \) being the thickness of the beam modifier independent of
the angle of the incoming particle.

2.1.5. Dose engine. The dose engine section contains three subsections. In the computation
subsection two different MC codes for the patient dose calculation are available: EGSnrc and VMC++.
A CT conversion can be selected from a number of different conversion schemes: the default EGSnrc
conversion, the conversion scheme used in our clinically used TPS, Helax-TMS (Nucletron B.V.,
Veenendaal, The Netherlands) and the two schemes investigated in a recent multi center study by
Vanderstraeten et al. [22]. Then the user is able to choose either to compute a pre-patient phase space
file, to compute the dose distribution for the selected fields (see 2.1.2.) in the patient or to load an already calculated dose file.

In a second subsection the desired voxel dimensions can be assigned for all directions. Based on these voxel dimensions an in-house written algorithm is used to re-sample the CT data. This re-sampling algorithm is based on hermite interpolation [23] and follows two basic requirements: First, the total integral of the interpolation function and the given data is equal, and second, sampling the same grid reproduces the original data set.

The variance reductions subsection consists of a couple of variance reduction methods which has yet been implemented only for the dose calculation algorithm VMC++.

2.2. MC calculation

After all parameters are set in the MC GUI, the execute button submits the MC calculation. Note that there are default settings for all parameters, thus if the default settings are suitable only the configuration name needs to be given. Based on the settings the MC calculation jobs are sent to a Linux environment (AMD Athlon 64 3400+, 2.4 GHz) using secure shell (SSH Communications Security, Ratingen, Germany). The SMCP framework keeps track on the status of the individual jobs until they are finished. The results of the dose distribution for each field will be sent back to the Windows PC, where the Research API is running. The latter returns the dose distribution field by field into Eclipse, where the dose distribution is displayed the same way as if the dose would have been calculated with any other algorithm available in Eclipse.

2.3. Validation and Applications

There are many possible applications of the SMCP framework of which a few are shown in this paper. Apart from examples of the comparison between open beam dose calculations and measurements, calculated MLC transmission values compared with measured ones using film (X-Omat V, Kodak, Rochester, NY) and an ionization chamber (RK 8305, Scanditronix Wellhöfer, Schwarzenbruck, Germany) are presented. For the MC calculations the phase space source and the VMC++ transport code has been used. The measurements for the transmission data have been performed in a water phantom at a depth of 5 cm. In a further application, the CPU requirement of the different transport techniques for the secondary collimator jaws with a 10×10 cm² field size is determined, demonstrating the possibility to investigate and optimize the beam modifier part. Additionally, two clinical cases are shown: The first case is a 3D conformal lung case using three 15 MV fields, each with a static MLC and a physical wedge. Isodose lines for the MC calculated dose distribution are compared with those for the dose distribution calculated using the Eclipse pencil beam algorithm within the plan evaluation task in Eclipse. The second clinical case is a H&N patient with four 6 MV intensity modulated fields applied using dynamic MLC. The MC calculated dose distribution as well as the dose volume histograms are compared with those calculated using the AAA algorithm. VMC++ is used for all patient dose calculations. The treatment plans within Eclipse have been normalized such that the mean dose of the planning target volume (PTV) receives the prescribed dose, which corresponds to 100%. Hence, this results in monitor units for each field calculated by Eclipse. Those monitor units were taken to set the corresponding monitor units for the MC dose calculations, i.e. Eclipse and the MC calculated dose distributions have been forced to have the same number of monitor units for each field in all the cases studied.

3. Results

3.1. MC GUI

Figure 2 and 3 show the results of the Qt implemented MC GUI for the general and the config tab, respectively. These tabs contain the sections which allow the settings of the parameters for the MC calculation as described in 2.1. The execute and the cancel button at the bottom of the MC GUI starts and cancels the MC dose calculation, respectively. The research tab includes some features mainly
used for special research or testing tasks, like using fixed seeds for the MC calculation or using a beta version of the framework implementation, etc. The last tab deals with settings regarding an amorphous silicon detector and is discussed in the work of Frauchiger et al. [24].

Figure 2. The MC GUI as it shows up after the Research API is started in Eclipse. The general tab is divided in a general setting section (top) and a field setting section (bottom).

Figure 3. The config tab of the MC GUI includes three main parts: the source setting (top left), the beam modifier part (top right) and the dose engine part (bottom).

3.2. Validation and Applications
Figure 4 shows calculated and measured dose distributions. In figure 4 (a) depth dose curves for field

![Figure 4](image-url)

**Figure 4.** Calculated (symbols) and measured (lines) dose distributions in water at a 100 cm source-to-surface distance. (a) 15 MV depth dose curves for field sizes of 3×3, 5×5, 10×10, and 20×20 cm², (b) 6 MV profiles for a 10×10 cm² field size at a depth of 1.5, 5, 10, 20, and 30 cm.
sizes of $3 \times 3$, $5 \times 5$, $10 \times 10$, and $20 \times 20$ cm$^2$ for 15 MV are depicted at a 100 cm source-to-surface distance (SSD). All the dose values at depths larger than that for the dose maximum agree within 1.5% relative to the maximum dose, except for those close to the depth of 40 cm. At those depths the calculation underestimates the measurement because of missing backscatter, since the water phantom for the MC calculation had a thickness of 40 cm. Figure 4 (b) illustrates the comparison of dose profiles for a field size of $10 \times 10$ cm$^2$ at depths of 1.5, 5, 10, 20, and 30 cm in water for the 6 MV beam at a 100 cm SSD. The dose values agree within 1.5% or 1.5 mm relative to the dose value at the central axis.

In figure 5 profiles of film measured and MC calculated transmission data are depicted at a depth of 5 cm in a water phantom perpendicular to the leaf motion direction and at a 100 cm SSD. The mean transmission values of the film measurements averaged over the two central leaves was 1.58% (6 MV) and 1.76% (15 MV) which corresponds to measurements of 1.59% and 1.78%, respectively, performed with an ionization chamber. Arnfield et al. [25] measured a transmission of 1.68% for the 6 MV beam, but for the Varian Millenium 120-leaf MLC. LoSasso et al. [26] found somewhat larger transmission values of 1.8% (6 MV) and 2% (15 MV), respectively. However, they investigated a 42-leaf pair MLC with slightly thinner leaves.

![Figure 5](image_url)

**Figure 5.** Calculated and measured MLC transmission profiles at a depth of 5 cm in water perpendicular to the leaf motion direction for a $10 \times 10$ cm$^2$ field. (a) 6 MV and (b) 15 MV.

Figure 6 demonstrates the possibility to investigate different transport techniques for the beam modifier part. The radiation transport through the secondary collimator jaws has been simulated for a $10 \times 10$ cm$^2$ field by the different transport techniques available. For each simulation the CPU time was determined for both 6 and 15 MV. The CPU times were evaluated relative to the CPU time required by EGSnrc which was set to 1. The CPU time requirements decrease as the level of complexity for the radiation transport decreases. This is more pronounced for the 15 MV beam compared with the 6 MV beam. This is because with increasing photon energy the energy of the produced secondaries increases and hence the CPU time spent on transporting secondaries increases. Thus, transport techniques which take only a simplified or no secondary particle transport into account save more CPU time when the 15 MV beam is used compared with cases using the 6 MV beam instead.
Figure 6. CPU time required for different transport techniques of simulating the radiation transport through the secondary collimator jaws for a 10×10 cm² field size relative to the CPU time EGSnrc required, which is set to 1. The insert shows the corresponding selection list within the config tab of the MC GUI (see figure 3).

Figure 7. Comparison of the isodose lines between MC (left) and pencil beam (right) calculated dose distributions, respectively, within the Plan Analysis task for the 3D conformal lung case.

The clinical cases demonstrate the usefulness to load the MC calculated dose distribution back into Eclipse (figure 7 and figure 8). The lung case is shown in figure 7. The typical differences for the isodose lines are observed leading to a penumbra broadening [27]. Furthermore, using the pencil beam dose calculation algorithm results in an overestimation of the high dose region, i.e. especially for the PTV [27-31]. Finally, figure 8 depicts the MC calculated dose distribution together with the dose
distribution calculated with the AAA algorithm for the H&N case. The center plot in the top row of figure 7 shows the corresponding dose volume histogram comparison. The AAA algorithm predicts a more homogeneous dose distribution within the PTV compared with the prediction when using the MC method. This observation corresponds with findings from other groups [32-34]. Furthermore, the dose values to the myelon and the left submandibula gland are higher using the MC dose calculation algorithm. The dose maximum for the myelon and the left submandibula gland increase from 21.6% and 71.6% for the AAA algorithm to 22.7% and 75.1% for the MC method, respectively.

![Figure 7](image)

**Figure 8.** Comparison of the isodose distributions between MC (left) and AAA (right) calculated dose distributions, respectively, within the Plan Analysis task for the intensity modulated Head and Neck case. In the middle the dose volume histograms are compared: the triangle belong to the MC calculation and the squares to the AAA calculation.

4. **Discussion and Conclusion**

In this work a flexible and efficient framework for photon MC treatment planning is presented. The framework is successfully interfaced with the Eclipse TPS. Overall several advantages have been achieved:

- suitable for clinical routine due to high efficiency
- benefit from the features in Eclipse
- benefit in terms of documentation and backup
- safe, since few user interactions necessary
- clear data structure
In principle it is possible to interface the framework also to other TPSs by replacing the Dicom streams with methods provided by the considered TPS. One possibility would be to use the normal Dicom in- and export, which is generally supported by all commercial TPSs. Furthermore, it is simple to extend the framework to additional beam energies and additional treatment units.

The applications of the SMCP framework given in this paper are examples only to demonstrate its usefulness. Hence, these examples have not the intention to represent full self-contained studies. This would go beyond the scope of this paper. However, each of the different tasks will be the subject of further detailed investigations.

The implementation of the SMCP framework has not only the advantages of using all the features included in the TPS, but also of the user friendliness and automation of performing an MC dose calculation for any patient stored in the patient database of Eclipse. Since the framework is structured in modules, it is possible to add modules keeping the system highly flexible and efficient. Additionally, the environment allows a widespread use for all kinds of investigations from timing and benchmarking studies to clinical patient studies.

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