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**Monte Carlo Study of Photon Beams
from Medical Linear Accelerators:
Optimization, Benchmark and Spectra**

by

Daryoush Sheikh-Bagheri

A dissertation submitted in partial fulfillment of
the requirements for the degree of
Doctor of Philosophy

Ottawa-Carleton Institute for Physics
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the Faculty of Graduate Studies and Research
acceptance of the thesis

**MONTE CARLO STUDY OF PHOTON BEAMS
FROM MEDICAL LINEAR ACCELERATORS:
OPTIMIZATION, BENCHMARK AND SPECTRA**

Submitted by

Daryoush Sheikh-Bagheri, B.Sc., M.Sc.

in partial fulfilment of the requirements
for the degree of Doctor of Philosophy

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ABSTRACT

BEAM is a general purpose EGS4 user code for simulating radiotherapy sources (Rogers *et al.* Med. Phys. 22, 503-524, 1995). The BEAM code is optimized by first minimizing unnecessary electron transport (a factor of 3 improvement in efficiency). The efficiency of the uniform bremsstrahlung splitting (UBS) technique is assessed and found to be 4 times more efficient. The Russian Roulette technique used in conjunction with UBS is substantially modified to make simulations additionally 2 times more efficient. Finally, a novel and robust technique, called selective bremsstrahlung splitting (SBS), is developed and shown to improve the efficiency of photon beam simulations by an additional factor of 3-4, depending on the end-point considered. The optimized BEAM code is benchmarked by comparing calculated and measured ionization distributions in water from the 10 and 20 MV photon beams of the NRCC linac. Unlike previous calculations, the incident e^- energy is known independently to 1%, the entire extra-focal radiation is simulated and e^- contamination is accounted for. Both beams use clinical jaws, whose dimensions are accurately measured, and which are set for a $10 \times 10 \text{ cm}^2$ field at 110 cm. At both energies, the calculated and the measured values of ionization on the central-axis in the buildup region agree within 1% of maximum dose. The agreement is well within statistics elsewhere on the central-axis. Ionization profiles match within 1% of maximum dose, except at the geometrical edges of the field, where the disagreement is up to 5% of dose maximum. Causes for this discrepancy are discussed. The benchmarked BEAM code is then used to simulate beams from the major commercial medical linear accelerators. The off-axis factors are matched within statistical uncertainties, for most of the beams at the 1σ level and for all at the 2σ level. The calculated and measured depth-dose data agree within 1% (local dose), at about 1% (1σ level) statistics, at all depths past depth of maximum dose for almost all beams. The calculated photon spectra and average energy distributions are compared to those published by Mohan *et al.* and decomposed into direct and scattered photon components.

STATEMENT OF CONTRIBUTIONS

The original ideas of this thesis, which are presented in the following 3 scientific papers to be submitted to *Medical Physics*, the official science journal of the American Association of Physicists in Medicine (AAPM), and an official science journal of the Canadian Organization of Medical Physicists (COMP) and the Canadian College of Physicists in Medicine (CCPM), are drafted and revised by the author of this thesis, who has performed, analyzed and discussed all the calculations. The measured ionization distributions used in chapter 3 are provided by the co-authors of the second paper.

- “Selective bremsstrahlung splitting: A robust method to improve the efficiency of photon beam simulations of linacs”, Daryoush Sheikh-Bagheri and D. W. O. Rogers, to be submitted to *Med. Phys.* (1999)
- “Monte Carlo study of dose distribution of the 10 and 20 MV photon beams of the NRCC linac”, Daryoush Sheikh-Bagheri, D. W. O. Rogers, C. K. Ross, and J.P. Seuntjens, to be submitted to *Med. Phys.* (1999)
- “A Monte Carlo study of photon beam spectra from medical linear accelerators”, Daryoush Sheikh-Bagheri and D. W. O. Rogers, to be submitted to *Med. Phys.* (1999)

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List of Symbols

BEAM: NRC *EGS4* user-code for Monte Carlo simulations of clinical radiation units;

CM: Component Module used in *BEAM* to define a specific class of geometric shape;

CPE: Charged particle equilibrium;

DOSRZ: NRC *EGS4* user-code for Monte Carlo calculations of cylindrical 2-dimensional dose distributions;

DOSXYZ: NRC *EGS4* user-code for Monte Carlo calculations of 3-dimensional dose distributions;

$D_{\max}$: maximum absorbed dose (usually on a depth-dose curve);

$d_{\max}$: depth at which $D_{\max}$ occurs, here also used for depth of maximum ionization;

ECUT: cutoff energy for electrons in Monte Carlo simulations using *EGS4* code (total energy, MeV);

EGS4: Electron Gamma Shower Version 4, a Monte Carlo code system;

ESAVE: the maximum charged particle energy (in MeV) at which range rejection is considered in *EGS4* simulations;

ESTEPE: the maximum fractional energy loss per electron step in *EGS4* simulations;

KD2: a model of Siemens accelerator;

$(\bar{L}/\rho)_{\text{air}}^{\text{water}}$: Restricted collisional spectrum-averaged mass stopping power ratio of water to air;

OAF: off-axis factor;

OMEGA: a project to develop electron dose planning using Monte Carlo simulation (Ottawa Madison Electron Gamma Algorithm);

PCUT: cutoff energy for photons in Monte Carlo simulations using *EGS4* code (MeV);

PEGS4: preprocessor for *EGS4*;

%*dd*: percentage depth-dose, the ratio of dose at a depth in phantom to the maximum value of dose;

%*dd*(10): percentage depth-dose at 10 g/cm² depth;

%*dd_x*(10): percentage depth-dose at 10 g/cm² depth from a pure photon beam (*i.e.*, no electron contamination);

PMA: Poly methyl methacrylate also called luciteTM or plexiglassTM;

P_{repl}: a factor that corrects for replacement of phantom material by an ionization chamber's cavity;

R_e: the distance from the central axis, projected onto a certain SSD, of the direction of travel of the electron in the target, used in SBS;

R_f: the radius of the field, to calculate the probability of bremsstrahlung emission into, used in SBS;

r_{inner}: the radius of the chamber cavity

SBS: Selective Bremsstrahlung Splitting;

SPR: Stopping-Power Ratio;

SPRRZ: *EGS4* user-code for Monte Carlo calculations of stopping-power ratios in cylindrical annuli;

Chapter 1

Introduction

1.1 Introduction

Cancer patients are treated by radiation, surgery, chemotherapy, or combinations of these three methods. Radiation has proven to be an effective treatment method for a variety of cancerous tumors. The history of treatment prescription began when the first treatments by radiation were performed. The first treatment charts date back to 1921: the very year when Marie Curie was offered one gram of Radium, while visiting United States, to be used for radium therapy. Radiotherapy progressed slowly during the following years on an essentially empirical approach. The British School and particularly the Manchester team, brought a major contribution to treatment planning in introducing methodical procedures in the set-up of the patient and in the evaluation of individual dose distributions. A first revolution occurred in the early fifties with the jump from conventional X-rays to high-energy photon beams. Betatrons and ^{60}Co units progressively replaced 200 kV X-ray machines. During the mid 1940s, one group in England and another at Stanford succeeded in building a linear array of coupled cavities capable of both transporting microwave power and accelerating injected electrons. Such pulsed travelling-wave linear accelerators could provide high average beam currents and large energy gains.² Later on, standing wave microwave electron linacs were developed for radiation therapy which obtain a given energy at a given microwave power in an accelerator of shorter length. For a good discussion on the advancements in linear accelerator design for radiotherapy see Karzmark.³

Megavoltage x-rays are created when high-energy electrons are stopped in a target material. The electrons are accelerated in a straight line in a linear accelerator (linac), as opposed to circular orbits used in betatrons and cyclotrons. The linac is mounted in a gantry which rotates on a stand containing electronic and other systems. The linac can be rotated into position about the horizontal gantry axis for use in treatment. The radiation beam emerging from the collimator is directed through and, for symmetric fields, centered on the gantry axis. The beam central axis intersects the gantry axis

at a point in space called the isocenter.

The characteristics of electron and x-ray treatment beams are strongly influenced by the design of the x-ray treatment head. For example, the design of the target and the flattening filter has a large influence on the uniformity of dose distribution achievable in a patient.⁴ In addition to a bending magnet, fixed shielding (*e.g.*, the primary collimator) and large movable collimators (*e.g.*, the jaws), the head contains the x-ray target, flattening filter, and in some cases dual electron scattering foils, usually mounted on a large carousel.

1.2 Radiotherapy with photons

The principal modality for the treatment of deep-seated tumors is high-energy x-rays with high penetrating power. Clinically, most tumors can be adequately irradiated with 4-6 MV x-ray beams.³ However, thick body sections like lateral pelvis are advantageously treated with 10-25 MV x-rays. On the other hand, electron beam irradiation is most useful in the treatment of superficial tumors, since energy is deposited close to the skin, quickly dissipating and sparing deeper tissue.

Radiotherapy is generally fractionated, *i.e.*, administered in fractions of 1.8 to 2.5 Gy/day, five days/week. Fractionation improves the therapeutic index (the margin of safety between therapeutic and toxic doses), presumably because sublethal radiation injury is repaired more effectively in normal tissues than in tumors.

Treatment planning is a necessary step to meet the goal of radiotherapy, that is to say, to eradicate a tumor without causing too severe a damage to healthy tissues. Treatment planning was gradually improved but dose distributions were calculated manually for each patient. The second revolution happened in the mid-sixties through the introduction of computers in radiotherapy.

1.2.1 Photon beam dose calculations

Dose calculation algorithms have been reviewed by several authors over the years.⁵⁻⁸ These algorithms can be classified based on the dimension of the scatter integration, method of inhomogeneity correction, and their relative computational efficiency. In a more unified approach, dose computations have been classified by Mackie *et al.* into correction-based and model-based algorithms,⁹ which will be discussed briefly. Calculations to predict the patient dose from photon beams used in radiotherapy have been traditionally based on correcting measured dose distributions in a homogeneous phantom. These methods are briefly described in section 1.2.1.1. More sophisticated dose algorithms are based on predicting the dose from first principles using a model of radiation transport. The two major algorithms in this category are convolution/superposition method and the Monte Carlo method, which are briefly discussed in section 1.2.1.2.

1.2.1.1 Correction-based algorithms

There are three general steps in computing the dose in a patient, using a correction-based algorithm:¹⁰

- ★ Representing the dose in a homogeneous medium using generating functions. This usually requires the following measurements: in-phantom central-axis depth dose, lateral dose profiles, beam output measurements in a phantom and in a miniphantom, and wedge factor measurements. An ion chamber is usually used as a detector. Examples of generating functions, derived from dose measurements are the tissue-phantom-ratio (TPR) and the off-axis-ratio (OAR).
- ★ Reconstituting the generating functions for the actual treatment field. For example, in the Clarkson¹¹ summation technique the dose is obtained by adding up contributions from individual beam elements. After the dose distribution is

reconstituted it is modified or corrected for the presence of beam modifiers (like wedges) and the patient anatomy. A correction factor is computed which is the ratio of the expected dose in the clinical situation to the measured dose. The correction factor is then multiplied by the measured (or reconstituted) dose to yield an estimate of the dose in the clinical situation. An example of this approach is the effective TPR method for tissue heterogeneity corrections.

- ★ Correcting for patient anatomy. The patient anatomy introduces complications, due to patient contour and tissue inhomogeneity. The correction for patient contours should take into account the effects of scatter as well as primary dose, but since primary dose dominates, simple corrections along the primary ray usually provide a first-order approximation. Examples of this, are the effective tissue-air-ratio (TAR) method, and the equivalent TAR method¹² which also considers the effective field size.

1.2.1.2 Model-based algorithms

There is no hard boundary between correction-based and model-based algorithms.¹⁰ The essential difference is that model-based calculations do not attempt to reconstitute measured data before correcting them for the patient treatment situation.¹⁰

1.2.1.2.1 Convolution/Superposition The convolution/superposition method has been applied extensively to external beam dose calculations.^{13–19} In this method the beam “intensity” distribution is convolved with a spatially invariant kernel. The Dose D , at a point $\vec{r}$ in 3-D space can be calculated from:

$$D(\vec{r}) = \int_V T(\vec{r}') A(\vec{r} - \vec{r}') d^3r' \quad (1.1)$$

where $T(\vec{r}')$ is the total energy released per unit mass (*terma*) due to primary photon interactions in a volume element d^3r' at a point $\vec{r}'$ in the absorbing medium, and

$A(\vec{r} - \vec{r}')$ is the energy deposition which describes the fraction of the interacting energy that is deposited at $\vec{r}$ by secondary particles originating at $\vec{r}'$ per unit volume. Term, $T(\vec{r})$, can be calculated analytically for a mono-energetic beam as

$$T(\vec{r}) = \left(\frac{\mu}{\rho} \right) E \Phi_0 \exp(-\mu d(\vec{r})) \quad (1.2)$$

where $d(\vec{r})$ is the depth below the surface and μ is the attenuation coefficient of the medium, E is the photon energy, Φ_0 is the photon fluence incident at the surface of the absorber, and ρ is the density of the absorber (assumed to be homogeneous here).

The energy deposition kernel is only *truly* spatially invariant in an infinite and homogeneous absorber that is irradiated by a monoenergetic beam, but these conditions generally do not occur in real situations. In realistic situations several factors can cause problems with the kernel approach, including differences in the radiological properties of the various tissues encountered, x-ray beam hardening, beam divergence; and charge particle contamination. To account for these factors, investigators have been forced to add superposition methods to their convolution techniques.^{13,18,20} Superposition is convolution with a spatially variant kernel.¹⁰ Superposition has improved the accuracy of convolution but increased the calculation time required.

1.2.1.2.2 Monte Carlo-based treatment planning If increased calculation time is justified to achieve the most accurate dose calculation, then one automatically thinks of the Monte Carlo method, which has been the gold standard in radiation dosimetry for the past few decades.^{5,8} Monte Carlo based treatment planning for megavoltage photon beams is becoming increasingly feasible due to cheap computing power. Monte Carlo simulations of photon beams are widely recognized as an essential tool for improving treatment planning²¹⁻²⁷ and accelerator design.²⁸⁻³⁰ Monte Carlo-based treatment planning is a two stage process: firstly, the beam generated by the linac is modeled, and secondly, this information is used to calculate the dose distribution in the patient. In other words, a prerequisite of treatment planning is knowledge of the treatment beam, independent of the dose calculation algorithm used

for treatment planning. Monte Carlo simulations of the linac will provide the most reliable representation of the treatment beam.

Monte Carlo calculations attempt to simulate the stochastic nature of particle-particle interactions by sampling from known particle interaction cross sections in a random fashion. To preserve the random nature of the processes being simulated, one needs a random number generator (RNG), capable of producing a sequence of random numbers which are truly independent and ideally never repeat. Digital computers cannot provide a truly random sequence of numbers but can calculate pseudorandom sequences. A simple RNG used in Monte Carlo calculations is of the form

$$I_{n+1} = (aI_n + c) \text{ modulus } 2^k \quad (1.3)$$

where I_n is the n th random integer in the sequence, a is the multiplier, c is the increment, and k is the number of bits in the integers of the computer. For an appropriate choice of a and c the sequence length can be as high as 2^k . For a 32-bit machine this provides a maximum sequence length of 4×10^9 .

The EGS4 code system uses a “Lagged-Fibonacci Method” pseudo random number generator, devised by Marsaglia and Zaman,³¹ with a cycle length of 2^{144} .

1.2.1.2.2.1 Electron and positron interactions modeled in the Monte Carlo technique Electrons and positrons interact via “soft” and “hard” collisions with matter. We’ll focus on the electrons for the moment. In soft collisions, an electron interacts with the electron cloud at large impact parameters and loses a small fraction of its energy and can cause excitation or ionization. In hard collisions, the energy transfer to the target electron is sufficient to set it in motion with substantial energy to cause subsequent ionization or excitation. These secondary electrons are sometimes referred to as knock-on electrons, and the interaction is specified by the Møller cross section, which treats both electrons as free. For a positron, the creation of a knock-on electron is modeled using the Bhabha cross section.

Both electrons and positrons can elastically scatter from the electromagnetic field of the nucleus. For incident energies of a few tens of keV or less, these interactions can be modeled as a series of discrete events, but for higher energies the number of such interactions becomes so large that their simulation as discrete events is almost impossible. Most electron transport algorithms use a condensed-history technique in which the electron is followed in a series of steps, and a multiple-scattering theory is used to group the individual elastic scattering events which occurred during the step. EGS uses the Molière multiple-scattering theory.^{32–36}

Inelastic scattering of electrons and positrons from the electromagnetic field of the nucleus is a very important process, which has been given the special name of *bremsstrahlung* from German *bremsen*: “to brake”, and *Strahlung*: “radiation”. During *bremsstrahlung*, the incident charged particle gives part or all of its energy to create a photon. If the photon’s energy is above a certain threshold, it is transported individually, otherwise, the corresponding energy is deposited locally.

Positrons can annihilate while in flight or at rest, in a collision with an electron. Annihilation leads to the creation of two photons which share the energy of the annihilated positron and electron.

1.2.1.2.2.2 Photon interactions modeled in the Monte Carlo technique

Photons interact with matter through a variety of energy-dependent interactions.

At low energies (around a few tens of keV), and specially for higher atomic number materials, the predominant photon interaction is the photoelectric effect, in which the photon is absorbed by a (usually K-shell) electron and the electron ejected from the atom leaving a vacancy. The vacancy can be filled by a higher-level electron for which the transition is allowed, which then emits a fluorescence photon. Although EGS has features to model fluorescence, it is ignored in this work due to its very small contribution at the photon energies involved.

At energies of the order of 1 MeV, the most likely interaction is Compton (or incoherent) scattering, in which the photon scatters from an orbital electron and sets it in motion. It is also the dominating process for low-Z materials over a wide range of energies. For example more than half the cross section from 25 keV to 25 MeV for carbon is Compton. While modelling Compton scattering (and at energies higher than diagnostic energies) it is adequate to consider the bound electron as free and ignore the effect of the binding energy on the cross section.

In contrast to Compton scattering, the photon scatters elastically from the atom in Rayleigh scattering. Rayleigh scattering constitutes no more than 1% of the cross section at energies above 200 keV in carbon (C), and in lead (Pb), for example, it contributes a maximum of 5% to the total cross section at energies between 0.1-1 MeV. Rayleigh scattering is ignored in this work.

At energies higher than a few MeV, pair production begins to dominate, where an electron-positron pair is produced when the photon is absorbed by the strong electromagnetic field of the nucleus.

With much less likelihood, a photon can also interact with the electromagnetic field of an orbiting electron, create a pair and transfer a considerable amount of energy to the orbiting electron. Therefore, this interaction is called triplet production. In EGS, the cross section due to a triplet interaction is included in the total cross section: however, the third e^- or e^+ is not followed.

Photonuclear interactions occur when a photon is absorbed by the nucleus and a nucleon is ejected. The resonance is centered at around 12 MeV for heavy nuclei and 24 MeV for light nuclei. Photonuclear interactions are usually ignored in radiotherapy simulations for two reasons:³⁷ firstly, the (γ, n) interaction often dominates the (γ, p) interaction (specially for high-Z materials), and neutrons don't deposit energy unless they undergo a nuclear interaction, and secondly, photon mean-free-paths are large enough compared to the dimensions involved in the simulation that the added increase

in the cross section (by modelling photonuclear interactions) will only have a minor effect.

Other rare and commonly ignored interactions are as follows: the double-Compton effect (where the photon scatters from an electron and another photon is also created in the process - the cross section, however, is included in the total Compton cross section), nuclear Thompson scattering (where the photon scatters elastically from the nucleus), and Delbruck scattering (where the photon scatters elastically from the Coulomb field of the nucleus).

1.2.1.2.2.3 Photon transport: an example An essential element of any Monte Carlo simulation is the ability to sample the various probability distributions which describe the physical processes involved and to simulate the random nature of these individual events. How are photons transported? Let's look at an example case: Let's assume that a photon to be transported in an infinite medium can only interact through Compton scattering or photoelectric effect. The total cross section is then expressed as the sum of the individual cross sections (at a certain energy, in units of cm^{-1}):

$$\sigma_{tot} = \sigma_{Compton} + \sigma_{photo}. \quad (1.4)$$

The mean free path of the photon is given by σ_{tot}^{-1} . We also know that the distribution of photon path lengths is an exponential function. Now if we select a random number R_1 uniformly distributed between 0 and 1, and define:

$$x = -\frac{1}{\sigma_{tot}} \ln(R_1), \quad (1.5)$$

then it can easily be shown that x is exponentially distributed between zero and infinity with a mean value of σ_{tot}^{-1} . In other words, the photon can be assumed to interact after traversing a distance equal to x . But what interaction will occur at x ? Compton or photoelectric? To answer this we generate a second random number, R_2 , again uniformly distributed between 0 and 1. Then we compare the ratio $\sigma_{Compton}/\sigma_{tot}$

to R_2 , if $R_2 \leq \sigma_{Compton}/\sigma_{tot}$, then a Compton interaction occurs at position x , or a photoelectric event otherwise.

1.2.1.2.2.4 The BEAM/EGS code system The BEAM^{38,39} code is a general purpose EGS4⁴⁰ code which is being widely used to model linear accelerators.^{41–48}

EGS4^{40,49} (Electron Gamma Shower version 4), is a simulation code to model an electromagnetic cascade shower in an arbitrary geometry for particles with energies above a few keV up to several TeV. The code was initially developed at Stanford Linear Accelerator Center (SLAC). Figure 1.1 shows a schematic diagram for the EGS4 code system. The code is divided into a “user code” and an “EGS code”. The user code contains the subroutines HOWFAR which defines the geometry, and AUSGAB which enables the user to extract information from the subroutine SHOWER, a subroutine which when called, results in the generation of one EGS history. The EGS code, by using Class II algorithms, differs from other Monte Carlo systems, such as *ETRAN*,^{50,51} *TIGER*^{52–54} and *CYLTRAN*.⁵⁵ Class II algorithms group the effects of only a subset of the interactions for each type and treat the effects of the remaining interactions on an individual basis, while Class I algorithms, group the effects (on the primary electron) of all interactions of a certain type together for each condensed-history step.³⁷ *ETRAN* uses a more complete set of bremsstrahlung production cross sections⁵⁶ compared to those presented by Koch and Motz (Bethe-Heitler and Schiff)⁵⁷ which EGS uses. Nonetheless, comparison of EGS4 calculated bremsstrahlung spectra with those calculated by using ITS version 2.1 (a general purpose version of *ETRAN*) has not shown a strong preference towards EGS4 or ITS.⁵⁸

Figure 1.2 presents a schematic of the overall steps required to do an accelerator simulation using the BEAM code system. At the specify-accelerator and build-accelerator steps, the user is instructing the system how to pull together the source code and make an execute module. At this stage, only a broad class of accelerator is defined (*e.g.*, which component to use to model the target or whether the flat-

Figure 1.1: Schematic diagram of the EGS4 code system, from Nelson *et al.*⁴⁰

Figure 1.2: The steps involved in using the BEAM system, from Rogers *et al.*³⁸

tening filter is upstream, inside or downstream of the primary collimator). During the execution stage, the program reads an input file which specifies all the details (*e.g.*, geometry and materials) about the particular accelerator. This input file specifies the specific materials in the accelerator or the phantom model for which the photon and electron cross section data are previously generated by the user, using the pre-processor for EGS called PEGS4. The input file also includes all the parameters controlling the radiation transport modeling and the various variance reduction techniques to be used.

The final stage of the simulation is the analysis of the outputs which consist of raw phase-space files (typically hundreds of Megabytes to Gigabytes in size, for photon beams), an output listing and (an optional) graphic of the simulation. The phase-space file is a direct-access binary file and each record in it contains the following information about a particle (in this order):

LATCH, E, X, Y, U, V, WT, (ZLAST)

where:

LATCH contains the particle charge, IQ, the number of times the particle has crossed the scoring plane, NPASS, and information which allows the particle's history to be traced. The value of LATCH in the phase space file is not the same as that internal to BEAM or other analysis codes because of the compression used.

E is the particle total energy (kinetic and rest mass, single precision)

X is the particle X-position (cm)

Y is the particle Y-position (cm)

U is the X-direction cosine

V is the Y-direction cosine

Using Spencer-Attix⁶¹ cavity theory, the dose to water can be found from the dose to gas. The general equation for dose to a medium is:⁵⁹

$$D_{\text{med}} = MN_{\text{gas}} \left(\frac{L}{\rho} \right)_{\text{gas}}^{\text{med}} P_{\text{ion}} P_{\text{repl}} P_{\text{wall}} \quad (\text{Gy}), \quad (1.7)$$

where $\left(\frac{L}{\rho} \right)_{\text{gas}}^{\text{med}}$ is the stopping power ratio of the medium to that of the gas, P_{ion} is the correction factor for recombination losses,⁶² P_{repl} is the replacement correction factor (it depends on the energy of the beam, the radius of the chamber), and P_{wall} accounts for the differences in composition between the medium and the chamber wall.^{59,63}

1.3 Overview of the thesis

The effect of linac design on photon beam quality, and consequently on the depth dose and its clinical implications has been investigated before.^{4,28,29,64} Various methods have been proposed to estimate photon beam spectra: using Laplace transforms of transmission data for orthovoltage^{65,66} and megavoltage^{65,67,68} x-rays, using depth dose curves measured in water,^{69,70} using various techniques of analysis of transmission data,⁷¹⁻⁷³ and using Monte Carlo calculations.^{1,74,75} In addition to photon spectra, Monte Carlo calculations provide the most complete analysis of a linac output.^{1,75-77}

1.3.1 Optimization

One major drawback of Monte Carlo simulation of linacs is the long calculation time required to obtain useful statistics. Although the BEAM code is already much faster⁴⁸ than other codes capable of simulating accelerators (*e.g.*, MCNP), it still takes a few days (on a single CPU) to obtain phase-space data of acceptable quality for dose calculations. Chapter 2 describes a systematic procedure to improve the efficiency of photon beam calculations with the BEAM/EGS4 code system. First, unnecessary

electron transport is minimized by using the standard range rejection technique in BEAM (see section 2.2 on page 23). This provides a factor of 3 improvement in speed. Then the uniform bremsstrahlung splitting (UBS) + Russian Roulette methods in BEAM (see section 2.3.2.1 on page 27) are improved and optimized. The improvement in efficiency using UBS, is about a factor of 4. The improved version of Russian Roulette (see section 2.3.2 on page 27), developed in this work, provides a consistent additional factor of 2 increase in efficiency.

Finally, selective bremsstrahlung splitting (SBS) is presented, as a novel and robust method to improve the efficiency of bremsstrahlung splitting by an additional factor of 3-4 (see section 2.3.3 on page 30).

These improvements are multiplicative so that BEAM's variance reduction techniques provide an overall improvement in efficiency of up to a factor of 100 to obtain high-quality photon phase-space, and up to a factor of 50 to obtain high-quality photon, electron and positron phase-space in a photon beam simulation.

1.3.2 Benchmarking of dose calculations

It is very important to benchmark calculations with the BEAM code since other Monte Carlo codes, like the Lawrence Livermore National Laboratory's PEREGRINE⁷⁸ project, use the BEAM code to simulate the top end of the accelerator, and thus base their results on BEAM.

The EGS4 code has been used by others to investigate dose distributions of megavoltage photon beams. Petti et al. investigated sources of electron contamination⁷⁹ and its effect on build-up dose⁸⁰ for a Clinac-35 25 MV photon beam. Lovelock *et al.*⁷⁷ also used EGS4 user codes to simulate Varian Clinac 600C and 2100C machines and compared calculated and measured central-axis depth dose distributions and profiles. However, no published Monte Carlo study so far has performed a systematic investigation of all the factors influencing the calculated dose distributions and demonstrated

agreement with measured values of central axis depth-dose curves at the 1% (1σ) level.

Chapter 3 aims at benchmarking photon beam calculations using the BEAM³⁸ Monte Carlo code against accurate measured dose distributions of both central-axis depth-ionization and ionization profiles at three depths. Important questions are: How well can measured values of ionization be matched by Monte Carlo calculations? And how do the uncertainties in the beam model translate to uncertainties in the calculated dose to the patient?

1.3.3 Commercial linac modelling

Chapter 4 describes how the BEAM code is applied to simulate the major commercial medical linear accelerators. Unlike the NRC linac where the electron beam energy and distribution are known, the proprietary nature of the specifications of commercial linacs does not allow the manufacturers to disclose this information freely. An iterative method of finding best estimates for electron beam energy and intensity distribution is used. Calculated off-axis factors and percentage depth-dose (%dd) values are compared with reliable measurements and two main parameters (the electron energy and radial intensity distribution) are varied until a match is found.

In chapter 4 photon spectra and average energy distributions are also calculated and compared with those published by Mohan *et al.*¹ (see section 4.4 on page 111).

Additionally the spectra are decomposed into direct, primary collimator-, flattening filter-, and jaw-scattered photon spectra. This provides information on how the major components of a linac affect the spectra.

Chapter 2

Optimization

2.1 Introduction

2.1.1 Computing Efficiency of a MC Calculation

The efficiency (ϵ) of a Monte Carlo calculation, with respect to a specific endpoint, can be defined as:^{37, 81–83}

$$\epsilon = \frac{1}{T \cdot \sigma^2} \quad (2.1)$$

where T is the total CPU time for the run and σ^2 is the variance of the end-point of interest, where all end-points are normalized per incident particle. In practice one uses s , an estimator for σ , in eq. 2.1. When variance reduction techniques are employed, the computing time, T , for a given number of histories may increase. However, the goal is to make the product $T\sigma^2$ (Ts^2) decrease, by reducing variance to a greater extent. Variance reduction techniques, generally speaking, increase the efficiency of a certain quantity, and not necessarily all quantities of interest.³⁷

Two common variance reduction techniques used in Monte Carlo photon transport problems are Russian Roulette and splitting, both originally proposed by⁸⁴ J. von Neumann and S. Ulam. The purpose of this work is to optimize the use of both these techniques, with an emphasis on an extended form of splitting, in simulations of photon beams from linacs.

For photon beam Monte Carlo calculations, which typically take an order of magnitude longer than their electron beam counterparts, variance reduction techniques become extremely important. For example, without the employment of a photon splitting routine, on average one needs to simulate 350, 10 MeV electrons to obtain a single photon in a $10 \times 10 \text{ cm}^2$ field at a distance of 100 cm from the target. On a Pentium Pro (200 MHz) CPU this takes about 0.75 second. In an electron beam, however, one only needs to simulate about 10 incident electrons to obtain one electron at the scoring plane. Additionally, when calculating dose in a phantom with a given uncertainty, one needs to simulate many more histories for a photon beam calcula-

tion compared with an electron beam calculation. Photons are generated through the bremsstrahlung process by bombarding a (usually) high-Z target with a high-energy electron beam. Simulating an electron history is very time consuming since the electron undergoes numerous interactions inside the target before it exhausts all of its energy. It would be desirable to minimize the number of electrons, necessary to be simulated, to obtain a certain number of photons. This is made possible by using bremsstrahlung splitting and Russian Roulette. Other investigators have also felt the necessity of employing variance reduction techniques in their simulations, e.g., a simple geometrical Russian Roulette technique for photons has been reported⁷⁷ to improve the efficiency by a factor of 2.5 (defined simply as N/T , where N was the unweighted number of photons). The essence of this technique is as follows: if a photon exiting the target is aiming outside of a region of interest, it is discarded with a probability P_{disc} , otherwise it's assigned a weight $1/(1 - P_{disc})$. The apparent improvement in efficiency occurs since less time is spent to follow both photons which have a smaller chance to reach the scoring zone, and also the electrons they set in motion. It is not clear whether or not Lovelock *et al.*⁷⁷ use a range rejection technique for secondary electrons. If range rejection was not used, then when employing it, the improvement in efficiency from using the Russian Roulette technique would become less. Additionally, a more rigorous study of efficiency (as done in this chapter) is required to show that employing the simple weighting routine does not have an adverse effect on the variance of the quantities of interest in the simulation.

To maximize the number of photons produced in the treatment field per simulated electron history, a splitting technique called bremsstrahlung (photon) splitting⁸⁵ was implemented in the NRC EGS4 user-codes. This is now an established method of improving efficiency of photon beam simulations with the BEAM code.³⁸ In bremsstrahlung splitting, when an electron in the target is about to emit a bremsstrahlung photon, instead of sampling only once from the corresponding energy and angular distributions, one samples N times, where N is a user defined parameter. Since the

weight of each photon is reduced by a factor of $1/N$, the weighted number of particles is preserved. The energy of the electron is reduced by an amount equal to the energy of one of the sampled photons. Although this violates the conservation of energy on an individual interaction basis, it results in the correct fluctuations in energy loss for electrons and in correct expectation values for photon energy and angular distributions. The ETRAN Monte Carlo code also employs a biasing technique for photon splitting which is implemented in a different manner, by enhancing the bremsstrahlung cross section.^{37,51}

In this work, a method called selective bremsstrahlung splitting (SBS) is presented where the splitting factor, N , is allowed to vary, unlike uniform bremsstrahlung splitting (UBS) where N is a constant. The idea behind selective splitting is to split more often when the probability of sampled photons reaching the treatment field is high, and less often when the probability is low. The variation of N depends on the photons, having a high or a low probability of being emitted inside the treatment field. Since the splitting factor is a variable, photons emitted by different electrons have different weights. A wide range in particle weights can itself cause degradation of variance, and reduction of efficiency.^{37,81} Especially troublesome is the existence of photons with large weights (“fat” photons) in a population of photons with low weights. In section 2.3.1.2 on page 26 we discuss a method to evaluate different SBS routines based on the number of “fat” photons they produce.

In SBS, the splitting factor is calculated based on the probability of the emitted photons reaching the treatment field. This probability depends on the electron energy and direction of travel at the time of emission, and on the collimation of the photon beam. A full set of these probabilities (for any electron energy and direction) are calculated before particles are tracked. The calculation involves integrating the bremsstrahlung cross section differential in angle (see Appendix A on page 142), over an appropriate range of angles corresponding to the angular extension of the treatment field as seen by the emitting electron. During the simulation, the probabilities

reaching the cutoff energy. Range rejection can be performed on a region by region basis; if the range to the cutoff energy is less than the distance to the nearest region boundary, the history is terminated and energy is deposited in the current region.

Range rejection introduces an approximation because, in terminating a charged particle's history and depositing all of its energy in the current region, it is assumed that any bremsstrahlung photon that would have been created by the particle, does not leave the current region. One should minimize inaccuracies resulting from this approximation, by defining a range rejection cutoff, *i.e.*, the maximum energy (in MeV) at which range rejection is considered. This choice depends on the incident beam energy and the materials that it is passing through. Range rejection, in the model of the target of an accelerator, is restricted to electrons having kinetic energies below 189 keV to affect bremsstrahlung production minimally. Elsewhere in the linac, on the other hand, electrons do not need to be followed to such low kinetic energies if they don't have a chance to escape from the region they are currently transported in.

In order to determine an optimum value for range-rejection cutoff, a series of simulations are performed, where the cutoff is varied and the amount of bremsstrahlung production in the linac recorded. As a new application of LATCH (see page 14 for a definition of LATCH), its bit number 19 is set whenever a bremsstrahlung interaction occurs anywhere other than the target. Then by comparing the amount of bremsstrahlung reaching the scoring plane, from anywhere in the linac but the target, the optimum value for range-rejection cutoff is found to be 1.0 MeV (rest mass included) for very low energy beams (4 MV) and 2.0 MeV for higher-energy beams. These cutoffs provide the largest saving in time, while consistent with a negligible loss in bremsstrahlung fluence from the linac (less than 0.2% in total).

2.3 Improvement of efficiency using bremsstrahlung splitting

2.3.1 Calculation of efficiency

The output of each of the BEAM simulations is a phase-space file (see section 1.2.1.2.2.4, page 14), scored at a distance of 100 cm from the upstream surface of the target. All end-points are histogrammed [*i.e.*, their frequency of occurrence in a certain range of values (a bin) recorded] by properly accounting for the weight of all the events in that bin. This means the content of a bin is the sum of the weights of all the entries in that bin. The uncertainty in each bin is equal to the square root of the sum of the squares of the weights in that bin. This is based on Poisson statistics and the assumption that the entries are uncorrelated. All the histograms of the end-points contain 100 equal-width bins to provide good resolution. The overall variance assigned to the end-point is estimated as the sum of the variances (square of the uncertainties) of all bins, normalized per total quantity of the end-point. Adding up variances in each bin, ensures a more proper estimate for the variance when the corresponding distribution of the end-point is not flat. For example, a photon fluence distribution differential in energy, is not uniform and if variance is calculated over the entire spectrum (as one single bin), it will be erroneous by not accounting for the inherent variation of energy within the spectrum.

Having estimated the variance of the end-point of interest in a proper fashion, Eq. 2.1 is used to calculate the efficiency.

2.3.1.1 End-points studied

The following end-points, which are all normalized per incident electron on the target, are considered in this study: fluence across the field differential in x-position

(*i.e.*, histogrammed with 100 bins of $0.1 \times 10 \text{ cm}^2$ area for a $10 \times 10 \text{ cm}^2$ field), fluence differential in energy calculated in a $4 \times 4 \text{ cm}^2$ region around the central axis, kerma weighted fluence differential in energy, calculated for the entire field, and, kerma weighted fluence differential in energy, calculated for a $4 \times 4 \text{ cm}^2$ region around the central axis. Often the ultimate end-point is dose to water, but dose requires a separate and extensive Monte Carlo calculation. However, collision kerma, which is equal to dose when there is charged particle equilibrium, is used in this study, since it can be readily calculated by weighting each photon by the product of its energy and the mass energy absorption coefficient of water at that energy. Kerma-weighted end-points have the advantage of putting more emphasis on the statistics of higher-energy photons. These photons are less frequently produced due to the bremsstrahlung cross section, but nonetheless play an important role in dose deposition in a phantom. The required values for mass energy absorption coefficient of water are obtained by linear interpolation of data from Hubbell and Seltzer.⁸⁶

2.3.1.2 “Fat” photons

Both splitting and Russian Roulette require adjusting the particle’s importance weight. In case of bremsstrahlung splitting, for example, a proper reduction of photon weights is necessary to conserve the actual number of photons produced in a bremsstrahlung process. In Russian Roulette, on the other hand, the weight of the surviving particle is increased to usually 1. As a result, in a typical photon beam simulation, one might encounter many events with small weights and a few events with much larger weight. In this study the major focus is on the photons and thus we have named photons with large weights, “fat” photons. “Fat” events have been previously noted to lead to underbiasing or overbiasing and erroneous results if not handled properly.⁸¹ In present work, “fat” photons introduce large uncertainties in photon-related quantities of interest, and consequently adversely affect the efficiency of the calculation.

2.3.2 Uniform bremsstrahlung splitting (UBS)

Since all bremsstrahlung photons are split by the same number when using UBS, one does not expect to encounter “fat” photons. However, when electrons set in motion by these split photons are subject to a game of Russian Roulette, second-generation photons are produced with weights substantially bigger than the first-generation photons. In the versions of BEAM released up to Oct. 1998, if an electron which survived Russian Roulette emitted a bremsstrahlung photon, that photon was not split, and was therefore assigned a weight which was N times bigger than the first-generation photon, where N is the splitting number. In addition to this, if an electron-positron pair survived the Russian Roulette game, it was consequently assigned a weight N -times bigger than the parent photon, then upon annihilation of the positron the two resulting annihilation photons had the same large weight and were “fat” photons. In the energy range encountered in medical linear accelerators, electron-positron pairs are frequently created by photons of sufficient energy (above 1.022 MeV). In the modified version of Russian Roulette the splitting of both second- and higher-generation bremsstrahlung photons as well as annihilation photons is allowed, as shown schematically in Figure 2.1, so that production of “fat” photons is minimized.. The process of splitting annihilation photons (like bremsstrahlung splitting) requires sampling the direction and energy (in the case of in-flight annihilation) of the photons repeatedly and reducing their weights accordingly to $1/N$, where N is the splitting factor.

2.3.2.1 Modifications to uniform bremsstrahlung splitting

A uniform splitting factor of about 10-20 was reported to increase the efficiency of photon beam simulations with the BEAM code by up to a factor of 10 (when using Russian Roulette).³⁸ However, the present study shows that in the absence of Russian Roulette, splitting factors of 20-100 are by about 10% more efficient than values below 20 (see Figure 2.2). A more detailed study shows that the efficiency increases rapidly

Figure 2.1: Schematic showing the bremsstrahlung splitting of first-generation photons, the Russian Roulette of secondary electrons, and the splitting of second generation bremsstrahlung, and annihilation photons (only when Russian Roulette is performed). The X's denote electrons which have not survived Russian Roulette and therefore have been terminated.

Figure 2.2: Variation of the efficiency with the splitting factor when using uniform bremsstrahlung splitting (UBS). The results are valid for all the end-points studied. In the absence of Russian Roulette (solid line), the efficiency is relatively insensitive to the splitting factor. However, when Russian Roulette is played on secondary electrons (dashed and dotted lines), the efficiency tends to increase when splitting is increased. The big fluctuations in the dashed line indicate the presence of “fat” photons when annihilation photons are not split. “Fat” photons are eliminated when both the higher-generation bremsstrahlung and annihilation photons are split, and when the electrons they set in motion are subject to Russian Roulette (dotted line), the efficiency improves consistently by more than a factor of two. All curves are normalized to no splitting (NBS). Field size is $10 \times 10 \text{ cm}^2$ in a 10 MV realistic photon beam.

as the splitting factor is increased from 1 to 10, and then after a value of 20 is reached, the increase in efficiency continues to happen at a much slower rate. Splitting factors larger than 100 do not further increase the efficiency. The use of UBS improves the efficiency by a factor of 4 (when Russian Roulette is not used), compared with simulations without bremsstrahlung splitting.

Russian Roulette, by minimizing unnecessary electron transport, and therefore minimizing CPU time, has the potential of further increasing the efficiency. However, studies performed here show that using BEAM's original version of Russian Roulette, causes the efficiency to suffer from drastic fluctuations (see dashed line in Figure 2.2) depending on the random presence or absence of "fat" photons (see section 2.3.1.2 on page 26). Using the modified version of Russian Roulette described above provides a consistent improvement in efficiency (see dotted line in Figure 2.2) of an additional factor of 2.

2.3.3 Selective bremsstrahlung splitting (SBS)

Bremsstrahlung angular sampling in EGS is based on the angular part of the Schiff cross section,⁵⁷ as described by Bielajew *et al.*⁸⁵ The Schiff cross section is based on many approximations⁵⁷ which can be violated at low electron energies. Nonetheless, these violations have been shown to have small effects in the accuracy of the calculated bremsstrahlung angular distribution⁷⁶ and yield^{76,87} studied for 10-30 MeV electrons incident on thick targets. The selective bremsstrahlung splitting method is based on the Schiff cross section (see Appendix A Eq. A.1 on page 143).

Figure 2.3 shows the angular distribution of photons of various energies emitted by 10 and 1 MeV electrons, incident on tungsten. The cross section drops very rapidly for high-energy photon emission. Nonetheless, the angular distributions are very similar for photons of different energies, as shown in panels (c) and (d), where the corresponding distributions of panels (a) and (b) are normalized to their peaks.

Figure 2.3: The angular distribution of photons of different energies, emitted by 10 MeV (a and c) and 1 MeV (b and d) electrons incident on tungsten, obtained from Eq. A.1 (see Appendix A on page 142). The curves are for the different photon energies shown at the corresponding peaks, and in c and d are normalized to show the similarity between the angular distribution of photons of different energies. The angular distribution of photons having half the energy of the emitting electron (thick line in each distribution) is taken as representative of the angular distribution of all photons, when calculating probabilities (again, see Appendix A on page 142).

For a 10 MeV electron, the photon angular distribution peaks at an angle of 1.6° for photon energies of up to 9.5 MeV. The peak shifts to an angle of about 2° for photons emitted with an energy of 9.9 MeV. In the case of a 1 MeV electron incident on tungsten (panels (b) and (d) of Fig. 2.3), the angular distribution of higher-energy photons peaks at angles up to 3° larger than the average of about 10° . The angular distributions are much wider compared with those of the 10 MeV electron, and higher energy photons are emitted at larger angles. However, as in the case of a 10 MeV electron, the angular distributions of photons of different energies are similar.

It is evident from Fig. 2.3 that the angular distribution of photons varies slowly with the photon energy. To reduce complexity, the angular distribution of photons with half the energy of the emitting electron (thick lines), is taken as representative of the angular distribution of all photons. This proves to be noncritical, since the selection of the radius of the field, R_f , as described in section 2.3.3.4, overshadows the details of the angular distribution.

Typical values for the probability, $P(R_e, E_e, R_f, SSD)$, of bremsstrahlung emission into a field of radius R_f located at a distance SSD from the target, for electrons of various energies (E_e) on the central axis and aimed at a projected radius R_e at a distance SSD, are shown in Fig. 2.4a. The calculation of this probability is described in detail in Appendix A on page 142. All the probabilities in Fig. 2.4 are plotted versus the projected radius R_e , which can be easily calculated from the angle the electron makes with central axis, θ_e , and SSD ($R_e = SSD \tan(\theta_e)$). For higher electron energies, bremsstrahlung emission is more probable at smaller angles (with respect to the direction of travel of the electron) (see Fig. 2.3). Therefore, photons emitted by lower-energy electrons have lower probability to be emitted towards the field even when the electron is aiming directly towards the field, but higher probability when the electron is aimed away from the field, as shown by Fig. 2.4a. Fig. 2.4b shows that increasing the field size, R_f , in the model, increases the probability of photon emission into the field. The effect of varying the SSD is shown in Fig. 2.4c.

Figure 2.4: Values of the probability of bremsstrahlung emission into a field of radius R_f (usually specified as the equivalent square field), when the electron is aimed at a projected radius R_e at a distance of 100 cm. The probability is calculated for (a) electrons of different energies, and (b,c,d) 10 MeV electrons, varying: (b) the field size (specified as square fields), (c) the SSD, and, (d) the target material (solid line: $Z=74$, dashed line: $Z=4$). When not specified, Z is always taken as 74 in all calculations.

As one expects, bremsstrahlung photons have a higher probability of reaching the field when the SSD is made smaller. Fig. 2.4d shows the relative insensitivity of the calculated probabilities to the atomic number of the target. The atomic number is hard-coded in the model and taken as that of tungsten, thereby reducing the number of inputs required for a given simulation.

Two methods of splitting are investigated, which are based on the geometrical probabilities of photon emission into the treatment field: method A and method B.

2.3.3.1 Method A

In method A, splitting is performed as a linear function of the probability of photon emission into the field, with a minimum splitting factor of N_{min} and a maximum splitting factor N_{max} :

$$(\text{Method A}) \quad N(R_e, E_e, R_f, SSD) = \max\left(N_{max} \frac{P(R_e, E_e, R_f, SSD)}{P(0, E_{max}, R_f, SSD)}, N_{min}\right). \quad (2.2)$$

where, $N(R_e, E_e, R_f, SSD)$ defines how many photons to sample when an electron of total energy E_e , aimed at a projected radius R_e at a distance of SSD, is about to undergo a bremsstrahlung event. $P(0, E_{max}, R_f, SSD)$ is the probability of photon emission into the treatment field when the electron points along the central axis at the time of emission, and represents the maximum value of all such probabilities in the simulation. Normalization by $P(0, E_{max}, R_f, SSD)$ ensures that N_{max} represents the actual maximum splitting factor in the problem. Panels a and b in Fig. 2.5 show values of N/N_{max} versus the projected radius at 100 cm SSD, for different electron energies. Panels a and b correspond to $N_{min} = 0$ and $N_{min} = 0.05 N_{max}$, respectively. The splitting routine shown in Fig. 2.5b is designed to minimize “fat” photons.

As discussed in section 2.3.1.2 on page 26, the presence of “fat” photons is detrimental to the efficiency. A bad choice of SBS parameteres can easily lead to production of “fat” photons. Panels a and c in Fig. 2.6 show a comparison of uncertainties

Figure 2.5: Comparison of the values of $N/N_{\max}$ for method A (see section 2.3.3.1 on page 34) and method B (see section 2.3.3.2 on page 37). The values of $N/N_{\max}$ are plotted for electrons of different energies versus the projected radius at 100 cm to which the electron's direction of travel is pointing at the time of bremsstrahlung. (a) method A when $N_{\min} = 0$, (b) method A when $N_{\min} = 0.05 N_{\max}$, (c) method B when $N_{\min} = 0$, and (d) method B when $N_{\min} = 0.05 N_{\max}$.

Figure 2.6: Comparison of uncertainties in photon fluence, in an $8 \times 8 \text{ cm}^2$ region inside a $10 \times 10 \text{ cm}^2$ field, for two SBS calculations when $N_{\max} = 200$, and (a) $N_{\min} = 1$, or (c) $N_{\min} = 10$. The distributions of the size of the corresponding error bars are shown in (b) and (d). Occasional presence of “fat” photons in a bin causes a large uncertainty in that bin. A gaussian is fit to the first half of the distribution and the number of error bars larger than $mean + 3\sigma$ taken as an indicator of the presence of “fat” photons. Panel (a) shows calculations without Russian Roulette and panel (b) shows calculations with Russian Roulette.

emitted outside the field of interest and into the collimators (*i.e.*, those emitted by low energy electrons) are split into a large number, therefore increasing the CPU time necessary to follow them and the secondary electrons they potentially set in motion in the collimators.

2.3.3.3 Dependence on the end-point

Figure 2.7 shows plots of variation of the efficiency of SBS as a function of the assumed radius of the field R_f , for an actual $10 \times 10 \text{ cm}^2$ field, without (panel a) and with (panel b) Russian Roulette of secondary electrons. In both cases all the curves are normalized to a UBS calculation with a splitting factor of 25, which itself is subject to the Russian Roulette game in panel b. When using SBS, with optimum values of N_{max} , N_{min} , and R_f (see next section), the efficiencies of calculating all of the end-points are increased by factors between 3 and 4. The amount of increase, unlike in the case of UBS, is dependent on the end-point. The efficiency is higher for the end-points calculated around the central axis compared to those calculated for the entire field. The efficiency is also higher for energy-weighted end-points like kerma-weighted fluence.

2.3.3.4 Dependence on the SBS parameters

Figure 2.8 shows the dependence of the efficiency on the various parameters of SBS. The results are based on a 10 MV beam from a realistic model of a medical linac. Panels (a) and (b) in Fig. 2.8 compare the efficiency of methods A and B, as one varies N_{max} when N_{min} assumes values of 1 and 10, respectively. The extreme fluctuations in efficiency when $N_{min} = 1$ (Fig. 2.8a) are caused by presence or absence of “fat” photons (see section 2.3.1.2 on page 26). The value of the circular field size, R_f , is taken as 11.3 cm in all panels of Fig. 2.8.

Figure 2.8c shows the effect of splitting all emitted photons by at least a factor of

Figure 2.7: Variation of efficiency for different end-points when in method A, the circular field size used to calculate the probability is varied. The actual field size is $10 \times 10 \text{ cm}^2$. The end-points depicted are as follows: $\Phi_{\text{entire field}}(x)$: fluence over the entire field differential in x-position (dashed dotted line), $\Phi_{\text{central}}(E)$: fluence differential in energy calculated in a $4 \times 4 \text{ cm}^2$ region around the central axis (dotted line), $K_{\text{entire field}}(E)$: kerma weighted fluence differential in energy, calculated in the entire field (dashed line), and, $K_{\text{central}}(E)$: kerma weighted fluence differential in energy, calculated in a $4 \times 4 \text{ cm}^2$ region around the central axis (solid line). $N_{\text{max}} = 1000$ and $N_{\text{min}} = 100$. Panel a shows calculations without, and panel b, with Russian Roulette.

Figure 2.8: Comparison of the variation of efficiency (in the absence of Russian Roulette) calculated using method A (solid line) and method B (dashed line) when $R_f = 11.3$ cm and $N_{\max}$ is varied and (a) $N_{\min} = 1$ and (b) $N_{\min} = 10$ (c) when $N_{\max} = 200$, $R_f = 11.3$ cm and $N_{\min}$ is varied, and (d) when $R_f = 11.3$ cm, but both $N_{\max}$ and $N_{\min}$ are varied ($N_{\min} = 0.1 \times N_{\max}$). The end-point for which the efficiency was calculated is kerma in a 4×4 cm region around the central axis in an actual 10×10 cm² treatment field.

N_{min} when N_{max} is kept constant at a value of 200. Although splitting all photons, including those which are going backwards, increases the CPU time, it decreases the variance to a larger extent. The variance is substantially decreased since the gap between photon weights is reduced and a more uniform distribution of weights is attained. It may be noted that once N_{min} is increased beyond a value of 6, the efficiency stays at a plateau. Figure 2.8d shows that one can still achieve further improvements in efficiency by increasing N_{min} proportional to N_{max} . The efficiency continues to increase, although at a slow rate, when N_{max} is increased to 1000 ($N_{min} = 100$). This increase is a combination of a reduction in the gap between photon weights and an increase in the number of photons produced in the field per incident electron on the target.

Based on the above mentioned results, the following values are recommended for SBS parameters for calculations in a 10×10 cm² field: A value of around 200 (or larger) for N_{max} , provided $N_{min} = A \times N_{max}$, where A is a factor between 0.05 and 0.1, and $R_f \approx 11$ cm.

2.3.3.5 Dependence on the treatment beam parameters

Is this method as useful in small and in large fields as it is for a 10×10 cm² field? Calculations show that for a field size of 1×1 cm², efficiency increases up to a factor of 4 are attainable, provided R_f is chosen between 10 and 25 cm. For a 40×40 cm² field, R_f doesn't need to be much larger than the actual field size. In fact the results show that $R_f \approx 25$ cm results in an optimum increase of a factor of 3.5 in the efficiency of calculation of kerma-weighted fluence around the central axis. The efficiency of calculating fluence in the entire field for a 40×40 cm² field improves by a factor of 2.5. An asymmetric 10×40 cm² field is also studied and as long as R_f is selected to cover the largest dimension of the field, improvements in efficiency are achieved which are as good as those for the 40×40 cm² field. As a rule of thumb, $R_f \approx \sqrt{(w + 10)^2/\pi}$, where w is the side of the field in cm for square fields and the

larger side of the field for asymmetric fields, results in close-to-optimum efficiency. For example, for a $10 \times 40 \text{ cm}^2$ field, R_f should be selected around 28 cm.

Improvements in efficiency similar to those for the 10 MV beam, studied extensively in this work, are also obtained for incident electron beam energies of 4 and 20 MeV.

2.3.3.6 Dependence on the linac

To be able to generalize the results obtained from studying one linac to simulations of all linacs, the dependence of the efficiency of the SBS routine on different beam energies and field sizes (see previous section) are studied. Additionally, in a series of simulations, the target thickness is increased from 0.1 cm to 0.5 cm and the same level of increase in efficiency is obtained. One other major difference in the construction of linacs is the flattening filter. The complexity of the flattening filter slows down the photon transport, since every photon's position has to be checked when it crosses the boundary of each of the layers of the flattening filter. The linac simulated in the SBS study had a fairly complex shape consisting of about 20 conical layers, making us confident in the validity of the results for commercial linacs with complex flattening filters.

2.4 Is the physics preserved?

Panels a and b of Fig. 2.9 compare kerma-weighted fluence differential in position, scored in a 2 cm wide band extended in the x-direction, calculated using UBS and SBS, respectively. The kerma-weighted fluences, differential in energy and calculated for a $4 \times 4 \text{ cm}^2$ region around the central axis using UBS and SBS, are shown in panels c and d, of Fig. 2.9, respectively. The CPU time for both methods was about 4.9 hours. It is evident that the statistics are improved appreciably using SBS. A

Figure 2.9: Comparison of kerma-weighted number of photons per incident electron (in MeV/g) in a real accelerator, differential in position and calculated for a 2 cm wide band extended in the x-direction (panels a and b), and differential in energy and calculated for a $4 \times 4 \text{ cm}^2$ region around the central axis (panels c and d). Panels (a) and (c) are calculated with uniform bremsstrahlung splitting (UBS) and panels (b) and (d) are calculated with selective bremsstrahlung splitting (SBS). The efficiency is improved by about a factor of 3 in (b) over (a) and a factor of 4 in (d) over (c).

Figure 2.10: Proof that SBS does not alter the physics of photon beam simulations. The ratio of kerma-weighted fluence per incident electron, differential in (a) energy, and (b) position, calculated using SBS and UBS is shown. A first order polynomial fit ($y(x) = A_0 + A_1x$) shows that there are no systematic differences between the two methods.

(a)

(b)

Figure 2.11: Proof that UBS, itself, does not alter the physics of photon beam simulations. The ratio of kerma-weighted fluence per incident electron, differential in (a) energy, and (b) position, calculated using UBS and NBS (no bremsstrahlung splitting) is shown. A first order polynomial fit ($y(x) = A_0 + A_1x$) shows that there are no systematic differences between the two methods.

Two SBS routines were investigated thoroughly and shown to improve the efficiency of calculating kerma to water in a realistic photon beam generally by more than a factor of 3 compared with the uniform bremsstrahlung splitting (UBS) routine.

The successful use of SBS requires proper selection of its user-selected parameters: R_f , N_{max} and N_{min} . The circular field size (R_f) is a user input parameter used to model the actual (usually non-circular) treatment field with a circular field of radius R_f , for which the probability of photon emission is more easily calculated. By selecting a larger circular field size, the probability of photon emission into this field will increase and fall off less rapidly as the electron aims away from the central axis as shown in Fig. 2.4b. In the case of asymmetric fields one must set R_f so that it will encircle the entire field. Another reason behind a substantial increase in efficiency when R_f is increased (see Fig. 2.7 and section 2.3.3.4), is the approximations used in SBS. An important approximation used is the assumption that all photons emitted by an electron will have sufficiently similar angular distribution to photons having half the energy of the electron. Although this assumption is on average valid, it underestimates the angular distribution of higher energy photons by a few degrees. However, its use eliminates an unnecessary integration over the energy of photons and increases the speed of calculating probabilities, substantially (see Appendix A, eq. A.2). The study of the efficiency for various field sizes ranging from 1×1 to $40 \times 40 \text{ cm}^2$, including asymmetric fields, shows that increases of at least a factor of 3 in kerma-weighted fluence are achievable, provided one chooses R_f sufficiently large: as a rule of thumb, $R_f \approx \sqrt{(w + 10)^2/\pi}$ is recommended, where w is the largest width of the field. The improvement in efficiency, in this case, originates from a reduction in the number of “fat” photons which reach the treatment field.

Another consequence of “fat” photons is that there can be a marked dependence of efficiency on the number of electron histories simulated. The sensitivity of the estimation of efficiency to the number of electron histories is investigated by varying the number of electron histories from 100000 down to 5000, and comparing simulations

which use SBS with those using UBS. Simulations with UBS show little dependence on the number of electron histories simulated as long as the number of histories is large enough (a few tens of thousands). In the case of SBS, however, the efficiency can depend on the number of electron histories simulated. If SBS parameters are not chosen properly, it is possible to have high efficiency in a short simulation (a few thousand electron histories) and then poor efficiency in a longer run (a few tens of thousand electron histories). This happens because in a long run, photons with generally high weights, produced through rare events, may occur more often. Nonetheless, if appropriate values for the SBS parameters are chosen and the presence of “fat” photons is minimized, even SBS becomes independent of the number of electron histories simulated.

A value of 200 is proposed as a close-to-optimum value for N_{max} for all cases studied here, provided a minimum value of 10 is chosen for N_{min} . If the minimum splitting factor (N_{min}) is chosen to be 1, both of the SBS routines result in a **decrease** in efficiency. This degradation, too, is a result of the occasional presence of a “fat” photon(s) (a photon with large weight, emitted by an electron which makes large angle with the central axis at the time of emission) in a group of otherwise low-weighted photons. One can, in principle, use larger values for N_{max} depending on the memory available, but accordingly one has to increase N_{min} to minimize “fat” photons. As a rule of thumb values for N_{min} between $0.05 - 0.1 \times N_{max}$ are recommended.

It is known that variance reduction techniques, to improve the efficiency of calculating a specific end-point, may lead to a degradation in the efficiency of calculating other quantities of interest in the simulation. Evaluations of the SBS routines are based on 4 physical quantities to ensure a method which is robust for all applications. These quantities are as follows: fluence differential in position, fluence differential in energy, fluence weighted by kerma differential in position in the entire treatment field and, fluence weighted by kerma differential in position in a small area around the central axis.

Two different splitting algorithms for SBS are investigated, and it is concluded that both methods lead to a similar level of improvement in efficiency (see Fig 2.8). Then one of the two methods (method A) is tested thoroughly for a variety of different cases, such as various field sizes, incident electron energies and linac configurations. By passing all these tests satisfactorily, method A has become the method of choice for SBS calculations.

It can be deduced from Fig. 2.7 that SBS preferentially improves the efficiency of production of high-energy photons. This is concluded since the kerma-weighted fluence (or in other words the energy- and mass energy absorption coefficient-weighted fluence) can be calculated up to 40% more efficiently than just the fluence. These photons are emitted just as the incident electrons enter the target, before they undergo major scattering events and lose some of their energy. The electron at this stage is also directed closer to the central axis and therefore the photons it emits have a higher chance to make it through the collimators and reach the scoring plane. This improves the efficiency by about 10% around the central axis compared to the entire field.

As a final check of the adequacy of SBS for high-precision dose calculations, method A is successfully used in the benchmark study of the 10 and 20 MV photon beams of the NRCC linac (see next chapter).

Chapter 3

Benchmark Study

with a FWHM equal to 1% of the nominal energy. The electron beam incident on the target is scanned on the surface of a cone with a half angle of $4.2^\circ \pm 0.3^\circ$ to obtain field flatness. The apex of the cone is positioned on the front face of the target, however, due to imperfections in the scanning coil, the apex wobbles. The wobble is estimated to occur inside a circle of 0.3 cm radius for the 10 MV beam and 0.2 cm for the 20 MV beams. The radial intensity profile of the electron beam is measured 11.5 cm upstream of the exit window using a profile monitor. The profile is estimated to be a Gaussian with a FWHM of 0.35 cm for the 10 MV beam, and 0.25 cm for the 20 MV beam. The inherent divergence of the beam broadens this profile by the time the beam reaches the target by about 0.05 cm.

Two ion chambers are used to monitor the linac output (see Fig. 3.1). Monitor M1 is built in-house and is essentially made of aluminium with a total mass thickness of 0.8123 g/cm². Monitor M2, consists of 6 aluminium-coated layers of kapton with a total mass thickness of 0.02164 g/cm².

The jaws (from a commercial accelerator) are nominally set to produce a geometrical 10×10 cm² field at 10 cm depth inside the phantom (see Fig. 3.1). However, when the exact lateral position of each jaw is measured it is observed that the inner surfaces (the sides enclosing the beam) of the various sections of the jaws, are not geometrically aligned on any side. A 0.34 cm thick slab of lead with a 15×15 cm² opening follows the monitor M2 to prevent backscatter into it. The front face of the water phantom (see section 3.2.2.1) is placed at 100 cm SSD from the upstream surface of the target.

The model of the 10 MV beam setup consists of (see Fig. 3.1) the electron exit window, the aluminium target and flattening filter, the upstream monitor chamber, the tungsten jaws with their measured settings, the downstream monitor chamber and the slab of lead. The jaws are assumed to be symmetrically set with respect to the central axis. The 20 MV beam setup is different only in two aspects (see Fig. 3.2): the target is thicker (4.5 cm) and no flattening filter is used.

NRCC, 10 MV photon beam

Figure 3.1: Components of the accelerator as used to generate the 10 MV photon beam. All dimensions are in cm. Values in brackets are the distances from the central axis to the inner edges of the openings, for both x- and y-collimators and have 0.05 cm uncertainty. The uncertainty in distances between the major components along the z-axis is about 1 mm.

Figure 3.2: Components of the accelerator as used to generate the 20 MV photon beam. All dimensions are in cm. Values in brackets are the distances from the central axis to the inner edges of the openings, for both x- and y-collimators.

The electron beam divergence is included in the model. An accurate assessment of the beam divergence is not possible, but it is estimated to be less than 5 mrad (specified at half-width at half maximum of the electron intensity distribution, see Fig. 3.3), which corresponds to a spread of 0.5 cm at 100 cm source-to-surface distance (SSD) and one would expect to see its effect on the profiles. An upper limit of 15 mrad (assigned to half maximum of the radial intensity distribution of the electron beam) is set on the beam divergence based on the geometry of the beam pipe and focusing magnets. It is assumed that electrons further away from the electron beam axis would make proportionally larger angles with the axis.

The intensity distribution of the electron beam is modeled as a Gaussian with FWHM of 0.45 ± 0.05 cm (for the 10 MV beam) and 0.33 ± 0.05 cm (for the 20 MV beam). These values include the effects of the electron beam divergence and the wobbling of the focal spot.

The air slab to the phantom, and the phantom itself are modeled using DOSXYZ (see section 3.2.3.2 on page 60).

3.2.2 Dose measurements

3.2.2.1 The water phantom

The phantom used for the dose measurements is a $50 \times 50 \times 50$ cm³ water tank with 1.72 cm thick polymethyl methacrylate (PMMA) walls, with a density of 1.19 g/cm³. The beam enters the phantom horizontally and passes through a 0.3 cm thick PMMA window, which bows by less than 0.02 cm due to water pressure. Since the reference depth is measured while the water is there, the distortion of the PMMA window is taken into account.

At each energy, 4 sets of dose measurements are performed; a central-axis depth scan, and 3 horizontal scans at 1.99 (10 MV only), 3.29 (20 MV only), 9.79 and 19.79

g/cm². The depths are effective depths of measurement in accordance with the IAEA protocol⁹⁹ and as discussed in the next section. The scanner is computer controlled with a placement precision of about 0.05 cm. The measured profiles at each depth are shifted horizontally to be made symmetrical with respect to the central-axis using difference plots of measured and calculated (symmetrical) values. The difference at each point is the difference between the Monte Carlo calculated values and the linearly interpolated values between the neighbouring measured data. When displaying the difference between calculations and measurements in those regions where no measured data are available, the difference is assigned a value of zero with zero size error bars to distinguish them from the other (meaningful) difference data.

3.2.2.2 The dose-measuring ion chamber

The ion chamber used in this study is a Semiflex Tube cylindrical chamber (PTW, Freiburg Germany, type 31002, formerly type 233642) serial number 396, with an active volume of 0.125 cm³ and a cavity diameter of 0.55 cm. The ion chamber's energy response per unit absorbed dose, as specified by the manufacturer, shows about 4% over-response to energies below 150 keV compared to ⁶⁰Co. If the energy response is assumed to stay flat for energies above that of ⁶⁰Co, the over-response at lower energies results in a 1% over-response inside the field and 3% outside the field at 10 g/cm² depth for the 10 MV beam. This is because the calculated average energy of all photons at 10 g/cm² depth drops from around 1.3 MeV inside the field to below 300 keV, starting 1 cm outside the geometrical edge of the field in good agreement with results measured by Fraass.¹⁰⁰ The average energy calculation is done using the DOSXYZ code modified in this work (see section 3.2.3.2 on page 60).

The effective point of measurement for the ion chamber has been taken as $0.75 \times r_{inner}$ upstream of the center of the chamber, consistent with the IAEA protocol,⁹⁹ where r_{inner} is the radius of the chamber cavity.

The finite size of the detector has two effects: (a) perturbation effects, and (b) signal averaging effects.^{101–108} The ion chamber being non-water equivalent perturbs the electron fluence which would be present in the water in the absence of the ion chamber. For central-axis measurements this is taken into account by considering that the effective point of measurement of the chamber is further upstream and not at its center. When measuring profiles and specifically in the penumbral region where there are highly non-linear gradients a correction is also necessary but this issue is not addressed in the current protocols for radiotherapy. Additionally, with a detector of finite size, like an ion chamber, what is actually being measured is the average signal over its entire active volume. This effect is assessed by convolving (basically averaging) the calculated profile with a square step having a width equal to the diameter of the ion chamber. This accounting for the spatial averaging effects of the ion chamber, changes the assigned dose at the geometrical edges of the 10 MV profiles by a maximum of 1.7% of maximum ionization (D_{max}) [at depth of maximum ionization (d_{max})]. At 20 cm depth the correction is almost negligible. At 20 MV the correction is no larger than 0.8% of maximum ionization.

3.2.3 Monte Carlo simulations

3.2.3.1 Accelerator simulation with BEAM

3.2.3.1.1 Simulation parameters Photons and electrons are transported down to energies of 0.01 MeV and 0.7 MeV (including rest mass), respectively. When a particle's energy reaches the above cut-off values, its energy is scored locally. Since low-energy electron transport constitutes a major part of the total CPU time for the simulation, BEAM's range rejection technique³⁸ is used. Anywhere outside the target, if the electron's total energy falls below 2.0 MeV (ESAVE) and its range does not allow it to escape the geometric region it is already travelling in, then it is discarded and its energy scored locally. The above value for ESAVE is selected since it provides

a factor of 3 increase in speed and ignores only 0.1% of photons reaching the phantom surface, produced due to bremsstrahlung anywhere in the linac except in the target. Range rejection is turned off in the target, to provide the most accurate model for bremsstrahlung production.

Calculations are performed initially with both uniform bremsstrahlung splitting (UBS) and selective bremsstrahlung splitting (SBS).¹⁰⁹ Dose distributions using both methods are statistically the same. These calculations prove SBS to be suitable for phase-space-based dose calculations. Subsequently, SBS is used in the rest of the simulations. Russian Roulette of secondary electrons is not employed, since both photons as well as contaminant electrons are of interest in the dose calculations. When using UBS, a splitting factor of 30 is used, and the following parameters are used with SBS: $N_{max} = 200$, $N_{min} = 10$, and $R_f = 11.3$ cm. As discussed in chapter 2 on page 19, the use of SBS results in improvements in efficiency of up to a factor of 4 compared to UBS.

3.2.3.1.2 Modeling of the electron beam To simulate the electron beam incident on the target properly, and to be able to investigate the effect of beam parameters (width, intensity distribution, divergence) a new source routine (ISOURC15) is written for BEAM. Figure 3.3 shows the swept beam source with radial distribution and divergence. The source allows one to sample incident electrons from a radially symmetric intensity distribution defined at a given plane perpendicular to central-axis (usually the apex of the sweeping cone, see below). Additionally, it allows one to assign a divergence to the beam and sweep the resulting beam on the surface of a cone with a given half angle. The divergence is simply specified as an angle at a certain radius (throughout this thesis, strictly at half-width at half maximum) of the radial intensity distribution of the electron beam.

The width of the electron beam when it reaches the target is 0.4 cm and 0.3 cm (FWHM) for the 10 and 20 MV beams, respectively. To also include the effect of

Figure 3.3: The geometry of ISOURC15 source, designed in this work. The beam sweeps on the surface of a cone with half-angle GAMMA and with the apex defined at ZFOCUS . The beam itself has a user-defined radial intensity distribution (in the case shown, a gaussian), defined at ZFOCUS and in a plane perpendicular to the Z axis. The beam then diverges from this original distribution as if it originated at an imaginary point back along the axis of each elemental beam. The position of this imaginary point is defined by the divergence angle, THETA_IN , and the radius (at ZFOCUS) at which the divergence angle is defined, RTHETA_IN . $\text{Z_min_CM}(1)$ specifies the plane where the incident particles (here the electrons) enter the geometry.

wobbling of the focal spot as mentioned above, these Gaussians are convolved with circles of radii 0.3 cm and 0.2 cm, producing Gaussians with FWHM of 0.45 cm and 0.33 cm, respectively.

3.2.3.1.3 Phase-space scoring The linac simulation is run in parallel on 30 Pentium Pro 200 MHz processors. For the 10 MV beam, a total of 6×10^7 and for the 20 MV beam a total of 1×10^7 electron histories are simulated. The 10 MV simulation ran at 670000 histories/hour on each CPU, whereas at 20 MV, 160000 histories/hour per CPU could be simulated.

The linac simulation produces phase-space files scored at a plane right behind the lead shield located at $z=56.385$ cm (see Fig. 3.1).

For the 10 MV beam the phase-space files contain 8 weighted and 870 unweighted photon entries per 1000 electrons incident on the target. At 20 MV the phase-space files contain 27 weighted and 4000 unweighted photon entries per 1000 electrons incident on the target.

3.2.3.2 Calculations with DOSXYZ

DOSXYZ is an NRC EGS4 user code to calculate dose in cartesian voxels. The geometry used in DOSXYZ is shown in Fig. 3.4. The phantom is divided into $3 \times 85 \times 41$ slices in the x, y, and z directions, respectively, resulting in 10455 voxels. The unequal divisions are to minimize the total number of voxels while maintaining good resolution where needed. The phantom includes the air gap between the linac and the water tank as well as the PMMA wall of the tank. In the water part of the phantom the voxels range in volume from 0.03 cm^3 to 104 cm^3 . Central-axis depth-dose is calculated in the $2 \times 2 \text{ cm}^2$ region around the central-axis. The width of the voxels in the penumbral region of the profiles is 0.1 cm.

In this work, DOSXYZ is modified to allow calculation of several physical quan-

Figure 3.4: Geometry used to calculate dose distributions with DOSXYZ and $(\bar{L}/\rho)_{\text{air}}^{\text{water}}$ distributions with SPRXYZ. The density of water is taken as 1 g/cm³.

tities of interest in addition to dose, including the energy fluence and average energy of primary and phantom scattered photons.

Calculations using the DOSXYZ code are run in parallel on 30 CPUs producing 30 output files for each quantity of interest. Each DOSXYZ calculation reads a corresponding phase-space file as input, recycling it less than 6 times for the 10 MV beam and less than 17 times for the 20 MV beam, and provides output files in ASCII format. These outputs are processed off-line to calculate the mean and standard deviations of each quantity using the array processing utility (SIGMA) of the PAW software (version 2.09/13) from CERN.¹¹⁰ The statistical uncertainties in dose at both depth of maximum ionization and 10 g/cm² are about 0.2%.

Since an ion chamber measures ionization and not dose (see section 1.2.2 on page 15), the calculated values for dose have to be converted to ionization, by correcting them for a series of correction factors including the ratio of stopping-power of water to air. No photon beam dose distribution study published so far, has taken account of the variation of stopping-power with position. However, the precision of this benchmark study requires a detailed study of the variation of stopping-power with position. This necessitates the use of the SPRXYZ code capable of calculating stopping power ratios for a realistic photon beam (including the electron contamination therein) in a *Cartesian* geometry (see next section). The SPRXYZ code is used to calculate values of $(\bar{L}/\rho)_{\text{air}}^{\text{water}}$ and then divide the value of dose in each voxel by the corresponding value of $(\bar{L}/\rho)_{\text{air}}^{\text{water}}$ to provide ionization. The variation of other correction factors in Eq. 1.7 on page 16 with the position in the beam is ignored in this work, and the value of dose corrected for the ratio of stopping-power of water to air is loosely called ionization.

3.2.3.3 Stopping power ratio calculations with SPRXYZ

A special code called SPRXYZ is written, which is a hybrid of the NRCC user-codes SPRRZ¹¹¹ and DOSXYZ, and which enables one to calculate stopping power ratios of realistic photon and electron beams in a Cartesian geometry. Comparison of calculations done with SPRXYZ with those done using SPRRZ, for values of $(\bar{L}/\rho)_{\text{air}}^{\text{water}}$ on central axis as a function of depth, shows good agreement.

Calculations at 10 MV show that the variation of $(\bar{L}/\rho)_{\text{air}}^{\text{water}}$ with depth amounts to 1.25% over the entire depth of the phantom. The value of $(\bar{L}/\rho)_{\text{air}}^{\text{water}}$ starts at 1.119 ± 0.001 just past the PMMA wall, rapidly decreases to 1.114 ± 0.001 at depth of maximum ionization, has a value of 1.113 ± 0.001 at 10 cm depth, and then gradually decreases to 1.106 ± 0.001 at 50 cm depth. The general trend just discussed (an increase close to surface and a very gradual decrease with increasing depth beyond depth of maximum ionization) is in agreement with calculations done by Andreo and Nahum.¹¹² Previous NRC calculations,¹¹³ of $(\bar{L}/\rho)_{\text{air}}^{\text{water}}$ which employed a point source emitting a 10 MV Mohan¹ spectrum from a 100 cm distant point in vacuum (*i.e.*, having no electron contamination), were done using the NRC SPRRZ code, and calculated a value of 1.114 at the surface and a value of 1.107 at 15 cm depth. These values compared to the calculations performed in this thesis, show differences of up to 0.5% in the build-up region mainly due to the presence of electron contamination. The difference between values of $(\bar{L}/\rho)_{\text{air}}^{\text{water}}$ inside and outside of the field in the 10 MV beam at the depth of maximum ionization, 10 and 20 cm depth, is 1.8%, 2%, and 2.7%, respectively.

At 20 MV the variation of $(\bar{L}/\rho)_{\text{air}}^{\text{water}}$ with depth amounts to 2% over the entire depth of the phantom. The value of $(\bar{L}/\rho)_{\text{air}}^{\text{water}}$ starts at 1.104 ± 0.001 just past the PMMA wall, rapidly decreases to 1.092 ± 0.001 at depth of maximum ionization, has a value of 1.091 ± 0.001 at 10 cm depth, and then gradually decreases to 1.082 ± 0.001 at 50 cm depth. The value of $(\bar{L}/\rho)_{\text{air}}^{\text{water}}$ inside the field in the 10 MV beam at depth

of maximum ionization, and at 10 and 20 cm depth, is 3.4%, 3.9%, and 4.5%, lower than outside the field, respectively.

Due to the very low energy of photons outside the field (see section 3.2.2.2 on page 56), the ion chamber is mainly detecting photons and not electrons, and therefore a correction for $(\bar{L}/\rho)_{\text{air}}^{\text{water}}$ in those regions may not be necessary. The $(\bar{L}/\rho)_{\text{air}}^{\text{water}}$ correction is applied throughout the phantom. Since the $(\bar{L}/\rho)_{\text{air}}^{\text{water}}$ is a relative correction, inside and outside the field, the absolute effect is so small that its effect on the dose profiles studied is not observable. For this reason the terms dose profile and ionization profile are used interchangeably throughout this chapter.

3.2.3.4 Normalization of data

The fall-off region (starting at 1 cm past depth of maximum ionization) of the calculated central-axis depth-ionization data are fit to a 4-th order polynomial using weighted least squares. Typical values obtained for χ^2 per degree of freedom are 0.6 - 0.7, at both energies. Using the fit, ionization data are normalized to a value of 1 at 10 g/cm² depth.

3.2.4 Factors studied

3.2.4.1 Electron beam energy

One advantage of using the NRCC linac in the benchmark study is that the electron beam energy is known to better than 1%, so it is not taken as a parameter. However, when the nominal beam energy is varied by 3% at 10 MV and 5% at 20 MV, it is observed that, unlike the peripheral dose (dose outside the penumbra), the dose distributions inside the field and in the penumbral region are sensitive to such variations. The beam energy, as one expects, also impacts the depth-ionization distribution and the calculations show that, for example, increasing the electron energy from 20 MeV

to 21 MeV changes the value of relative depth ionization at 10 g/cm² depth, from 0.788 ± 0.001 to 0.796 ± 0.001 .

3.2.4.2 Electron beam energy distribution

To assess if the electron beam energy distribution (which is taken as a Gaussian) has an observable effect on the dose distribution, a calculation done with a mono-energetic 20 MV beam is compared to our Gaussian model (with 1% energy spread) and no statistically significant differences in the central axis depth-dose or dose profiles are observed at the 1% (1σ) statistics level.

3.2.4.3 Electron beam radial intensity distribution

Fig. 3.5 shows the effect, in the 10 MV photon beam, of ignoring the radial intensity distribution of the electron beam and simulating it as a pencil beam of radius 0.001 cm, instead of a gaussian with FWHM of 0.45 ± 0.05 cm. This comparison demonstrates the necessity of modeling the electron beam radial intensity distribution. As expected, the penumbral width gets wider when the source size is increased, making the profiles systematically different in the penumbral region.

3.2.4.4 Electron beam sweeping angle

Calculations with the sweeping turned off (i.e., zero sweeping angle) show that the sweeping angle has an immense effect on the entire shape of the profile. To check the sensitivity of the calculations to the sweeping angle more accurately, the sweeping angle is changed from 4.2° to 4.1° . Calculated dose profiles with the sweeping angle of 4.1° are higher by up to 3% in the shoulder region, *i.e.*, inside the geometrical edges of the field, but not different outside. This provides a more precise (compare to $4.2 \pm 0.3^\circ$ in section 3.2.1) estimate for the sweeping angle and shows that it must

Figure 3.5: Comparison of the dose profiles calculated at depth of maximum ionization (d_{max}) in the 10 MV photon beam with (solid line) and without (dashed line) modeling the intensity distribution of the incident electron beam on the exit window. There are statistically significant differences, as shown by the inset, both inside and outside the geometrical edges of the field (vertical lines).

be $4.2 \pm 0.05^\circ$.

3.2.4.5 Electron multiple scattering in the target

To see whether the results are sensitive to the details of the electron multiple scattering in the target, ESTEPE (the fractional energy loss per step)⁴⁰ was reduced to 0.5%. Reduction of ESTEPE results in smaller electron multiple-scattering step sizes. The step size, which by default is determined by the PRESTA algorithm, depends on the dimensions of the voxels. Selection of the step size by PRESTA can lead to energy losses per step of typically a few percent (7% at 10 MeV in tungsten), or even 25% in large regions in water. Again, the results show no sensitivity to ESTEPE at the 1% (1σ) statistics level.

3.2.4.6 Cable current

Due to the lack of appropriate shielding of the beamline of the NRCC linac, cable current from the ion chamber can contribute a substantial amount to the signal when the ion chamber is scanning the regions outside the field. By shielding the main parts of the beamline with a lead wall this effect is minimized to a few tenth of percent of maximum ionization.

3.2.4.7 Secondary collimators

Since the inner surfaces of the secondary collimators are not necessarily aligned, the opening of each individual jaw at both the upstream and downstream faces are measured and the measurements used in the simulations. Shifts as small as 0.05 cm in the lateral position of back of the front jaw, located at $z=39.01$ cm, changes the ionization in the penumbral region by up to 4% of maximum ionization.

Since the penumbra is partially shaped by transmission through the edges of the

jaws the exact composition of the jaw might have observable effects. The composition of the jaws are varied from pure tungsten to a tungsten alloy (10.7% Cu, 32.2% Ni, 57.1% W, by weight) and no difference is observed in the profiles.

The primary transmission through the bulk of the jaws is estimated to be negligible (less than $10^{-5}\%$).

3.2.4.8 Other factors

The ionization recombination correction, P_{ion} , (see section 1.2.2 on page 15), for the chamber used in this study is assessed through the full/half bias voltage method⁵⁹ and is found to be 1 to better than 0.5%. Due to its small effect its variation with dose rate is ignored. The polarity correction factor is typically 0.1%. All the measurements are done with positive potential applied to the central electrode and variations in the polarity effect are ignored.

3.3 Results

3.3.1 Phase-space analysis

The phase-space data scored at 100 cm SSD (in addition to those scored behind the jaws), provide histograms of absolute photon fluence differential in energy (Fig. 3.6) and differential in position (Fig. 3.7). Note that the phase-space files analyzed in Figures 3.6 and 3.7 are 9 times smaller than those used in the dose calculations. At both energies the statistical uncertainty in photon fluence inside the field, for the actual phase-space files used in the dose calculations, is about 0.2% (for a 1 cm² region).

Figure 3.7: Photon fluence distributions at 100 cm SSD for the 10 (solid line) and 20 MV (dashed line) beams, for a 2 cm wide strip centered on the y axis. Note that the phase-space files analyzed are 9 times smaller than those used in the dose calculations.

3.3.2 Central-axis depth-ionization

3.3.2.1 The 10 MV photon beam

Figures 3.8 and 3.9 show comparisons of the Monte Carlo calculated values of central-axis ionization with the ion chamber measured values corrected for the effective point of measurement, for the 10 MV beam. The agreement past depth of maximum ionization is better than 0.7% of local ionization. Due to the normalization procedure used here, the effect of the correction factors only shows up in the buildup region (see figures 3.9 and 3.11). Correcting for the effective point of measurement has much greater impact on the depth-ionization curve than correcting for $(\bar{L}/\rho)_{\text{air}}^{\text{water}}$. For example, if one assumes that the effective point of measurement is $0.6 \times r_{\text{inner}}$ upstream of the centre of the ion chamber, then the agreement in the build-up region will become better than 0.45% of local ionization (see Fig. 3.10). The value of $0.6 \times r_{\text{inner}}$ is in agreement with the new recommendations of IAEA.¹¹⁴

At 10 MV, the calculated value for the ratio of dose on central-axis at 10 g/cm² depth to that at depth of maximum ionization is 0.682 ± 0.001 and that of ionization is 0.683 ± 0.001 , the measured value for ionization at 10 g/cm² depth is 0.682 ± 0.002 (0.689 ± 0.002 if the effective point of measurement is ignored). The error estimates on the measured values are based on an estimate of 0.05 cm accuracy in the position. The ratio of the dose at 20 g/cm² to that at 10 g/cm², D_{20}/D_{10} , in the 10 MV beam, is 0.587 ± 0.001 , based on the calculations and 0.584 ± 0.002 , based on the measurements. The dose from contaminant electrons constitutes 1.23 ± 0.03 % of maximum dose on the surface of the phantom (in the PMMA window) and 0.32 ± 0.02 % of maximum dose at the depth of maximum ionization.

Figure 3.8: Comparison of the calculated (solid lines) and measured (dashed lines) depth-ionization curves in the 10 and 20 MV photon beams. All curves are normalized to a depth of 10 g/cm² using a 4th order polynomial fit. The measurements are corrected for the effective point of measurement using a shift equal to $0.75 \times r_{inner}$, upstream of the centre of the ion chamber.

Figure 3.9: Comparison of the calculated (solid line) and measured (dashed line) depth-ionization curves in water for the 10 MV photon beam in the buildup region. The measured values (dashed line) are corrected for the effective point of measurement using a shift equal to $0.75 \times r_{inner}$, upstream of the centre of the ion chamber. All curves are normalized at a depth of 10 g/cm^2 using a 4^{th} order polynomial fit. The calculated depth-dose curve (dotted line) and the measured ionization not corrected for the effective point of measurement (dash dotted line) are also shown. The calculated curve for ionization is obtained by dividing the calculated values of dose by values of $(\bar{L}/\rho)_{air}^{water}$ calculated using the SPRXYZ code.

Figure 3.10: Comparison of the central-axis depth ionization for the 10 and 20 MV beams, when the shift, upstream of the centre of the ion chamber, due to the effective point of measurement is taken as $0.6 \times r_{inner}$ (a and c), and when it is taken as $0.75 \times r_{inner}$ (b and d). The 20 MV beam clearly demonstrates that the former choice results in much better agreement in the build-up region.

3.3.2.2 The 20 MV photon beam

At 20 MV the depth-ionization curves agree to better than 0.3% of local ionization past depth of maximum ionization, and better than 1.55% of local ionization in the build-up region (see Figures 3.8 and 3.11). Here it can be seen that although correcting for the $(\bar{L}/\rho)_{\text{air}}^{\text{water}}$ has a minor effect compared to the effect of the effective point of measurement, nonetheless, it has an observable effect and it slightly worsens the agreement in the buildup region, when the shift for the effective point of measurement is taken as $0.75 \times r_{\text{inner}}$. Nonetheless, as in the case of the 10 MV photon beam, correcting for the effective point of measurement has much greater impact on the depth-ionization curve than correcting for $(\bar{L}/\rho)_{\text{air}}^{\text{water}}$. For example, if one assumes that the effective point of measurement is $0.6 \times r_{\text{inner}}$ upstream of the centre of the ion chamber, then the agreement in the build-up region will become better than 0.5% of local ionization (see Fig. 3.10).

At 20 MV, the calculated value for the ratio of the dose on central-axis at 10 cm depth to that at depth of maximum ionization is 0.787 ± 0.001 and that of ionization is 0.788 ± 0.001 , the measured value for ionization at 10 cm depth is 0.785 ± 0.002 (ignoring the effective point of measurement this value would be 0.792 ± 0.002). The ratio of dose at 20 g/cm² to that at 10 g/cm², D_{20}/D_{10} , in the 20 MV beam, is 0.641 ± 0.001 , based on the calculations, and 0.642 ± 0.002 , based on the measurements. The dose from contaminant electrons constitutes 2.70 ± 0.04 % of maximum dose on the surface of the phantom (in the PMMA window) and 1.10 ± 0.03 % of maximum dose at depth of maximum ionization.

It is interesting to note that none of the factors studied affects the value of $\%dd(10)$, except, of course, the electron beam energy (see section 3.2.4.1 on page 64).

Figure 3.11: Comparison of the calculated (solid line) and measured (dashed line) depth-ionization curves in water, for the 20 MV photon beam in the buildup region. The measured values (dashed line) are corrected for the effective point of measurement using a shift equal to $0.75 \times r_{inner}$, upstream of the centre of the ion chamber. All curves are normalized at a depth of 10 g/cm^2 using a 4^{th} order polynomial fit. The calculated depth-dose curve (dotted line) and the measured ionization not corrected for the effective point of measurement (dash dotted line) are also shown. The calculated curve for ionization is obtained by dividing the calculated values of dose by values of $(\bar{L}/\rho)_{air}^{water}$ calculated using the SPRXYZ code.

3.3.3 Ionization profiles

3.3.3.1 The 10 MV photon beam

Figures 3.12, 3.13, and 3.14 show comparisons between measured and calculated ionization profiles at 1.99, 9.79 and 19.79 g/cm² respectively. The agreement between calculations and measurements is better than 1% (of maximum ionization), within 1 cm inside the geometrical edges of the field. As one approaches the penumbra, the agreement worsens at all depths. The worse case is at the depth of maximum ionization (see Fig. 3.12), where maximum differences of about 5% (of maximum ionization) are present. Because of the very steep dose fall-off in the penumbra, a slight misalignment of the jaws can lead to differences of the order seen here. The discrepancy between the position of the calculated and the measured penumbra is about 0.05 cm at depth of maximum ionization, and a maximum of 0.15 cm at 19.79 g/cm² depth. The discrepancy in the peripheral dose distributions is about 0.3% (of maximum ionization) at depth of maximum ionization, but it reduces to less than 0.2% (of maximum ionization) at 19.79 g/cm² depth.

3.3.3.2 The 20 MV photon beam

The calculated profiles at 20 MV show essentially the same kind of agreement with the measurements as at 10 MV. Figure 3.15 shows the comparison at depth of maximum ionization. The discrepancy around the geometrical edges is evident in this case too, but the profiles match slightly better in the regions well outside the edge.

3.4 Discussion and Conclusions

A very precise set of benchmark comparisons of Monte Carlo calculated dose distributions in 10 and 20 MV photon beams are performed. The agreement between

Figure 3.12: Comparison of the calculated (solid line) and measured (dashed line) ionization profiles at depth of maximum ionization ($d_{max} = 1.99 \text{ g/cm}^2$) for the 10 MV photon beam. Both curves are normalized to the value of ionization at 10 g/cm^2 depth on central-axis. The vertical lines show the geometrical edges of the field.

Figure 3.13: Comparison of the calculated (solid line) and measured (dashed line) ionization profiles at 9.79 g/cm² depth for the 10 MV photon beam. The Monte Carlo calculated values are corrected for the variation of $(\bar{L}/\rho)_{\text{air}}^{\text{water}}$ across the field. Both curves are normalized to the value of ionization obtained from a 4th order polynomial fit to the fall-off region of the corresponding depth-(dose or ionization) curves as shown in Fig. 3.8. The secondary collimators are set to provide a 10 × 10 field at this depth. The vertical lines show the geometrical edges of the field.

Figure 3.14: Comparison of the calculated (solid line) and measured (dashed line) ionization profiles at 19.8 g/cm² depth for the 10 MV photon beam. The vertical lines show the geometrical edges of the field.

Figure 3.15: Comparison of the calculated (solid line) and measured (dashed line) ionization profiles at $d_{max} = 3.3 \text{ g/cm}^2$ depth for the 20 MV photon beam. Both curves are normalized to the value of ionization obtained from a 4th order polynomial fit to the fall-off region of the corresponding depth-ionization curves as shown in Fig. 3.8. The secondary collimators are set to provide a 10×10 field at this depth.

Reduction of ESTEPE to 0.5%, from the default value defined by the PRESTA algorithm, shows no difference in the dose distributions, indicating that the results are not sensitive to the details of electron multiple scattering in the target.

The agreement, in the build-up region on the central axis, between calculations and measurements at both energies, will be better than 0.5% of local ionization at all depths, if a value of $0.6 \times r_{inner}$ (instead of $0.75 \times r_{inner}$) is used to correct for the effective point of measurement of the ion chamber.

The calculated ionization profiles agree with measurements to better than 1.2% of maximum ionization, inside the field more than 1 cm from the geometrical edges of the field. The agreement outside the field is better than 0.5% of maximum ionization. The agreement around the geometrical edges is better than 5% of maximum ionization and any agreement better than this, in that region, is likely coincidental and due to counteracting effects of a series of inaccuracies in the simulation parameters used in the linac model.

Chapter 4

Photon beam spectra from medical linear accelerators

4.1 Introduction

A Monte Carlo simulation of a commercial linac, in the ideal case, is only as good as the specifications of the linac. These specifications are hard to get, especially due to the proprietary nature of the information. In addition to this, these specifications are subject to mistakes, undocumented linac updates and large uncertainties in the most important parameters needed for the simulation, *e.g.*, electron beam energy and intensity distributions. The goal of this work is to derive best estimates for these parameters, by comparing calculated and measured values of off-axis factors (the ratio of dose rate at that point to the dose rate on the central axis, at a given SSD, usually 100 cm) and central-axis relative depth-dose (%dd, the ratio of dose at a depth in phantom to the maximum value of dose). This work focuses on the simulation of a “generic” linac for each beam energy and linac make. Most of the relative depth-dose comparisons, in this work, use the compiled measured data (consisting of both off-axis factors and relative depth-dose values) of task group 46 (TG-46)¹¹⁵ of the American Association of Physicists in Medicine (AAPM). For Philips machines the data published by Palta¹¹⁶ are used, since unlike TG-46,¹¹⁵ they include the build-up region. TG-46¹¹⁵ compares its compiled relative depth-dose with those of Palta¹¹⁶ past depth of maximum dose and the data agree to better than 0.8% for a 10×10 cm² field. Due to the lack of relative depth-dose data for the Siemens KD machine at 18 MV in the TG-46¹¹⁵ data base, careful measurements performed by Siemens scientists (Dr. Alf Siochi, personal communication) for this beam are used. In all cases, the relative depth-dose data are assumed to be measured and corrected properly, although this is often not the case. For example, careful measurements require the relative depth-dose data to be corrected for the point of measurement and the variation of $(\bar{L}/\rho)_{\text{air}}^{\text{water}}$ with depth, as discussed in section 3.2.2.2 on page 56 and section 3.2.3.3 on page 63.

The process of finding the “right” set of simulation parameters (*e.g.*, electron beam energy, radial distribution, divergence, energy distribution, angle of incidence)

dose data.

Sections 4.2 and 4.3 describe in more detail how the off-axis factors and relative depth-dose values are calculated and compared with measurements.

Once a set of parameters is found which leads to a match with both off-axis factors and relative depth-dose values, then the corresponding photon spectra at 100 cm SSD and for a $10 \times 10 \text{ cm}^2$ field are compared to those published by Mohan *et al.*¹ (see section 4.4 on page 111). Mohan's spectra are calculated only for Varian Clinac machines and in an open field.

4.2 Matching off-axis factors

In a megavoltage photon beam, flattening filters are used to obtain beam flatness across the field. The flatness, which is defined at a certain depth (usually 10 cm) in a phantom, varies with depth due to non-uniformity of the energy spectrum of the bremsstrahlung photons across the field and change in scatter. To obtain acceptable flatness (*e.g.*, at 10 cm depth), areas of high dose, called horns, near the surface at off-axis points have to be present.¹¹⁷ The flattening filter design causes the average energy and consequently the depth dose to be lower at off-axis points. This has been discussed by numerous authors.^{118–126}

Other investigators using Monte Carlo techniques have used dose profiles to derive the electron beam energy incident on the target.⁷⁷ In this work, in-air off-axis factors are used since they are relatively more sensitive to the electron beam parameters and the geometry of the simulation and are easier to calculate, since they do not require a second in-phantom Monte Carlo simulation.

4.2.1 Definition

The in-air off-axis factor at a distance x_j from the central axis, is defined as the ratio of dose rate at that point to the dose rate on the central axis, at a given SSD (usually 100 cm). The off-axis factors are measured in air with an ion chamber with full build-up to provide charged-particle equilibrium (CPE). The ion chamber measures the ionization of air which can be converted to dose to water as discussed in section 1.2.2 on page 15. Any variation in ion chamber response per unit dose across the field, due to variations in beam quality, is ignored. The off-axis factors are calculated using the water-kerma-weighted photon fluence, knowing that water kerma and dose to water are equal when there is CPE. In each of the 20 Monte Carlo calculations ($i = 1 \dots 20$, distributed on 20 CPUs, see Appendix B section B.0.1 on page 147) the water-kerma-weighted photon fluence (y_{ij}), scored in 15 annular bins ($j = 1 \dots 15$), are histogrammed versus radii uniformly ranging from 0 to 35 cm. The off-axis factor in the j -th radial bin, OAF_j , is then defined as:

$$OAF_j = \frac{\bar{y}_j}{\bar{y}_1} \quad (4.1)$$

where

$$\bar{y}_j = \frac{\sum_{i=1}^N y_{ij}}{N}. \quad (4.2)$$

The uncertainties in OAF_j are assessed in the standard form which is presented in Appendix B on page 148. Water-kerma is calculated by weighting each photon event by the product of its energy, the mass energy-absorption coefficient calculated at that energy, and the inverse cosine of the angle it makes with the z-axis. This weighting procedure ensures that there are no binning artifacts. The mass energy-absorption coefficient for water is obtained from linear interpolation of data from Hubbell and Seltzer.⁸⁶ It is assumed that the fluence is constant over the central bin, therefore the content of the first bin, y_1 is assigned to $x_1 = 0$, but for all the other bins the x_j represent the *center* of the corresponding bins.

4.2.2 Computational considerations

The off-axis factor calculations required between 5×10^5 (25 MV) and 5×10^6 (4 MV) initial electron histories, to obtain 1% statistics in the first bin ($0 \leq r \leq 2.33$ cm). At 4 MV the off-axis factor linac simulation ran at 4.5×10^5 histories/hour. For the 25 MV simulation this number was 4.7×10^4 histories/hour. The splitting (see section 2.3.3 on page 30) parameters for the off-axis factor simulations are as follows: $N_{max} = 400$, $N_{min} = 40$, $R_f = 50$, and a modified version of Russian Roulette (see section 2.3.2.1 on page 27) is used which causes annihilation photons to be split and Russian Roulette be played on the electrons they set in motion.

The relative depth-dose calculations use the BEAM code's CHAMBER component module since it has a more efficient range rejection technique compared to other NRC codes, such as DOSRZ or DOSXYZ, which calculate depth dose values. The water phantom is 25 cm in radius, is 50 cm deep and is divided into 0.5 cm thick depth-slices, except the first slab which is 0.25 cm thick. Dose is calculated in the central region of the phantom which has a radius of 1 cm. The dose calculations are also processed in parallel and result in 20 separate sets of dose distribution files. Each set consists of up to 10 dose components based on the LATCH bits represented in the component. When all the distributed calculations are finished, the results are combined into one set of (up to) 10 dose component files. The main components are the total dose and the electron contamination dose. The splitting parameters for all linac simulations needed to calculate relative depth-dose (in a 10×10 cm² field), are as follows: $N_{max} = 400$, $N_{min} = 40$, $R_f = 30$, and Russian Roulette is switched off, since in the case of dose calculations one is interested in good statistics for both photons and electrons. No photon interaction forcing is used. The values of ECUT and PCUT in all the simulations are 0.700 and 0.010 MeV, respectively. Range rejection is turned on with an ESAVE value of 0.7 MeV in the target for all beams and a value of 1.0 MeV in the rest of the linac for the 4 MV simulations and a value of 2.0 MeV for the rest of the linac for all the higher-energy beams. These values

are based on the range-rejection study, reported in section 2.2 on page 23. The linac simulations ran between 3.1×10^5 histories/hour at 4 MV, and 2.8×10^4 histories/hour at 25 MV; nonetheless, the number of photons in the $10 \times 10 \text{ cm}^2$ field per hour varies much less (using data from table 4.6 on page 134). A total of 1.6×10^7 and 5×10^5 electron histories are run for the 4 and 25 MV linac simulations, respectively. The total number of particle records (not weighted) in each of the 20 phase-space files, and therefore not restricted to the actual field, averages 1.13×10^5 photon records and 500 electron and positron records at 4 MV, and 6.3×10^4 photon records and 900 electron and positron records at 25 MV. Each subsequent dose calculation reads between 2×10^7 (4 MV) and 5×10^6 (25 MV) entries from the corresponding phase-space file, recycling the phase-space file 50-200 times. The ISMOOTH feature of BEAM is not used. Due to the enormous³¹ sequence length of the random number generator used, it is impossible that the sequence of random numbers will exactly line up for the few times a particle is being reused for the dose calculation and therefore recycling the phase-space is unlikely to lead to biased results. However, if the phase-space under-samples the actual underlying physical distributions, then recycling will lead to biased results. For example, if the spectrum of photons incident on the phantom is missing high-energy photons, then no matter how often the phase-space is recycled, it will not lead to the right dose distribution. Therefore the statistics of the phase-space must be good enough to represent all classes (*e.g.*, photons vs. electrons, or scatter vs. direct) of particles. Basically, the statistical uncertainty one can achieve in the dose calculation can not be better than the statistical uncertainty in the underlying phase-space. Tables 4.3, 4.4, and 4.5 below on pages 124, 125, and 126 present the tabulated photon spectra and show that the precision of the calculated fluence spectra for all the beams used in the dose calculations is high and that the uncertainty in each 250 keV wide bin is usually between 1 and 4%, except for the high-energy end of each of the spectra. The uncertainty in the photon fluence on the central axis (in the first radial bin, $0 \leq r \leq 2.25 \text{ cm}$) in the 4 MV simulation is 0.2 % and in the 25 MV simulation is 0.4 %. The dose calculation ran at 1.26×10^7 histories/hour at 4

MV, and 1.11×10^7 histories/hour at 25 MV.

4.2.3 Sensitivity to e^- beam mean energy

The off-axis factors are very sensitive to the electron beam energy and that's why they are selected here (along with relative depth-dose data) to derive the right electron beam energy incident on the target. Some manufacturers are generally vague when it comes to specifying the exact energy of the electron beam and in some high-energy beams the difference between the nominal accelerating potential and the specified incident electron beam energy is quite large (see Table 4.1). They also state that their specified energies are only starting points for the Monte Carlo simulation and therefore are only recommendations. Furthermore, tuning of the linac, after delivery to a cancer clinic, can change the energy of the electron beam incident on the target. Therefore, the user has to find the right value for the energy of the electron beam and justify it. Figure 4.1 shows a series of off-axis factor calculations performed when the incident electron beam energy is varied in steps of 0.1 MeV. The value of off-axis factor at 15 cm is selected from the calculations shown in Fig. 4.1 and plotted against energy of the incident electron beam, as shown in Fig. 4.2. The relationship is linear and the off-axis factor at 15 cm radius for this beam drops $-0.091 \pm 0.007 \text{ MeV}^{-1}$ as the energy of the beam is increased. The drop, to first order, results from the decrease in the mass scattering power (the angular deflection of the electron per unit mass thickness) with increasing energy. A simple calculation shows that a 1 MeV increase in energy results in more than 10° reduction in the average scattering angle of an electron incident on a 0.1 cm thick slab of tungsten. The angular distribution of bremsstrahlung photons also becomes wider as the energy of the electron is decreased (see Fig. 2.3 on page 31), but the bremsstrahlung cross section varies more slowly with the electron energy compared with electron mass scattering power. The combination of both these factors boosts up the value of the off-axis factor on the central axis relative to off-axis points, or in other words, upon normalization to the value of dose

Table 4.1: Characteristics of the electron beams used in the photon beams studied in this work. E_e is the mean energy of the electron beam incident on the target. Both the distribution of the electron energy and the electron radial intensity are gaussian in shape. The energy spread is given at FWHM. Both off-axis factors and central-axis relative depth-dose values are used to derive the electron beam mean energy and the FWHM of its radial intensity distribution. Note that the electron beam energy spread is not derived but taken as that nominally specified by the manufacturers. The modeled electron beams are incident normal to the target and have no divergence.

linac	nominal potential (MV)	nominal E_e and spread MeV	derived E_e and spread MeV	nominal e^- beam FWHM (cm)	derived e^- beam FWHM (cm)
Varian Clinac low-energy	4	4 (3%)	3.8 (3%)	0.1	0.10
Varian Clinac high-energy	6	6 (3%)	6.0 (3%)	0.1	0.15
	10	10 (3%)	10.5 (3%)	0.1	0.15
	15	15 (3%)	14.8 (3%)	0.1	0.15
	18	18 (3%)	18.3 (3%)	0.1	0.11
Philips	6	6 (17%)	6.2 (17%)	0.1	0.10
SL25	25	19 (5%)	18.5 (5%)	0.1	0.10
Siemens	6	5.53 (14%)	6.5 (14%)	0.2	0.40
KD	18	12.87(14%)	13.5(14%)	0.2	0.20

Figure 4.1: An energy sensitivity study around 6 MeV. The energy of the incident electron beam is varied from 5.5 to 6.6 MeV in steps of 0.1 MeV, with an energy spread of 1% at FWHM. The off-axis factor decreases with energy in a linear fashion (see Fig. 4.2).

Figure 4.2: The off-axis factors at 15 cm (from Fig. 4.1) are plotted vs. the energy of the incident electron beam. The data are fit to a straight line of slope -0.096 ± 0.007 with a χ^2 per degree of freedom of about 1.6.

on the central axis, reduces the horns.

The relative depth-dose curves can (and should) also be used to find the correct electron beam energy. The difference method used in this chapter enhances the sensitivity of a relative depth-dose comparison appreciably. Using this method, variations in the energy of the electron beam of about ± 0.3 MeV produce observable changes in the shape of the central-axis relative depth-dose curve, provided the uncertainty in dose at each point is about 1% (1σ) or better. The energy resolution provided by comparing off-axis factors is also about ± 0.3 MeV (see Fig. 4.2) when the uncertainty in the off-axis factor at each point is about 1% (1σ).

4.2.4 Sensitivity to e^- beam radial intensity distribution

The electron-beam radial intensity distribution influences the off-axis factors to a great extent. Generally speaking, the larger the width of the electron-beam radial intensity distribution, the relatively more intense the photon beam on the central axis. As in the case of the electron beam energy, most manufacturers do not provide an accurate description of the electron beam radial intensity distribution. Often one is told that the distribution can be assumed a gaussian with a FWHM of around 0.1 cm (see Table 4.1). Therefore, the radial intensity distribution of the electron beam is assumed here to be a gaussian with a FWHM taken as a free parameter. Figure 4.3 shows a series of calculated off-axis factors for a series of electron beams. The FWHM of the electron beam radial intensity distributions are varied from 0.01 cm to 0.19 cm in steps of 0.02 cm. To quantify the dependence of off-axis factors on the FWHM of the intensity distribution of the electron beam, the values of off-axis factor at 15 cm (obtained from Fig. 4.3) are plotted versus FWHM in Fig. 4.4. Fig. 4.4 shows that the off-axis factor drops quadratically with increasing FWHM of the electron-beam radial intensity distribution.

The off-axis factors drop rapidly when the FWHM of the electron intensity distri-

Figure 4.4: The off-axis factors at 15 cm (from Fig. 4.3) are plotted vs. the FWHM of the radial intensity distribution of the electron beam incident on the target. The solid curve shows a quadratic fit to the calculations, with a χ^2 per degree of freedom of about 0.7.

bution is increased, since more of the bremsstrahlung emitted at larger angles (relative to central axis) gets blocked by the primary collimator's upstream opening. This reduction in off-axis intensity translates into a relative boost on the central axis as seen in Figs. 4.3 and 4.4.

The central axis relative depth-dose values, on the other hand, are quite insensitive to such variations in the electron beam intensity distribution. The reason is that the shape of the central axis relative depth-dose, (ignoring the e^- contamination), is primarily determined by those photons which are incident around the central axis itself.

4.2.5 Sensitivity to e^- beam energy distribution

As in the case of the electron-beam mean energy and intensity distribution, manufacturers' specifications for the electron-beam energy distribution (see Table 4.1) can only be taken as a first estimate.

Since the off-axis factors are very sensitive to the mean energy of the electron beam, one would expect the actual energy distribution of the electron beam to be important too. Figure 4.5 is an attempt to clarify this point. At 6 MV, the FWHM of the electron-beam energy distribution is varied from 0 to 20%. No correlation is observed between the off-axis factors and the electron beam energy spread. This can be explained by noting that if both multiple-scattering and bremsstrahlung of an electron of energy $E - \delta E$ result in production of photons at an angle $\theta + \delta\theta$ with respect to the central axis, then electrons of energy $E + \delta E$ will result in photons travelling at an angle of $\theta - \delta\theta$, since both mass scattering power and bremsstrahlung cross section vary smoothly and slowly, in the same direction, with energy. In other words, one expects the variation introduced in the angular distribution of photons by electrons of higher energy to be cancelled by those having lower energy, leaving the final distribution similar to that emitted by monoenergetic electrons with a median energy.

Figure 4.5: Variation of off-axis factors at 6 MV, when the energy spread of the electron beam incident on the target is varied from monoenergetic (solid line) to 5 (dashed line), 10 (dotted line), 14 (dash-dotted line), and 20% (thin-solid line) energy spread at FWHM. When the values of off-axis factor at 15 cm are plotted versus the FWHM of the energy distribution, no correlation is observed.

However, this can only be true if only first order effects are considered, and in general, due to the non-linear variation of attenuation and scattering with energy, some differences should be observable. As an example, the relative depth-dose values show a small sensitivity to the electron beam energy spread, especially at larger depths. But since this sensitivity is not large enough to be conclusive, the electron beam energy spread is taken in the simulations as nominally specified by the manufacturers.

4.2.6 Sensitivity to e^- beam divergence

Since the electron beam radial intensity distribution has an important effect on the off-axis factors, one would expect the electron beam divergence to also play a role. The divergence of the electron beam is modeled as a smoothly varying function of the radial position of the electron with respect to the central axis and it is specified at half-width at half maximum of the electron radial intensity distribution throughout this thesis. To study the effect of divergence on the off-axis factors, for an electron beam with an intensity distribution FWHM of 0.1 cm, the divergence is varied from none to an angle of 1° , specified at a radius of 0.05 cm from the axis of symmetry of the electron beam. Up to a divergence of 0.5° at a radius of 0.05 cm, and at 0.3% statistics level, no difference in the calculated off-axis factors is observed. When the divergence is set to 1° at 0.05 cm, the off-axis factor at 15 cm radius decreases by close to 1% for an 18 MV beam. This is because bremsstrahlung emitted by a more divergent electron beam is blocked more efficiently by the primary collimator, reducing the value of off-axis factor at further off-axis points. The divergence of the electron beam incident on the target in commercial linacs is ignored in the simulations of this chapter.

The relative depth-dose shows insensitivity to a divergence of even 5° at half-width at half maximum (0.05 cm) of the electron beam intensity distribution, at 1% (1σ) statistics level.

4.2.7 Sensitivity to the upstream opening of the primary collimator

The primary collimator is one of the components of the linac influencing off-axis factors in a dramatic way. The details of the geometry of the primary collimator are much better known (and specified by the manufacturer) than for example, the electron beam energy and intensity distribution. Therefore, the primary collimator geometry is not taken as a parameter in the simulations, and is only varied to show the size of its effect. This influence mostly occurs at the upstream opening of the primary collimator where the opening restricts the fluence of bremsstrahlung photons originating from the target and contributes to the scattered photons reaching off-axis points further downstream. For example opening (or closing) the primary collimator's upstream opening by 0.01 cm, results in a 1% increase (or decrease) in off-axis factor at 15 cm, in an 18 MV photon beam (see Fig. 4.6). Therefore, the exact opening of the primary collimator must be known to much better than 0.01 cm when studying off-axis factors.

4.2.8 Sensitivity to material and density of the flattening filter

The material and the density of the flattening filter also influence the off-axis factors immensely. For a 15 MV beam, the flattening filter is simulated as if made of Cu, Pb or W. The off-axis factor at 15 cm, calculated with the Cu-flattening filter is 50% lower than that calculated assuming a W-flattening filter, and the corresponding value using a Pb-flattening filter is 33% lower (see Fig. 4.7). This sensitivity is primarily due to differences in the density. Even a flattening filter of a certain material can have different densities depending on the process used to manufacture it. For the same energy, the density of the W-flattening filter is decreased by 1 g/cm³ and it is

Figure 4.6: Figure showing the sensitivity of off-axis factors to a variation of 0.01 cm in the upstream radius of the primary collimator. The upstream radius of the primary collimator is varied from 0.236 cm (solid line) to 0.246 cm (dashed line) and to 0.226 cm (dotted line). The radius of the electron beam is assumed to be 1 mm. The filled squares are measured data.

Figure 4.7: The sensitivity of off-axis factors to the material the flattening filter is made of: Cu with a density of 8.933 g/cm^3 (solid line), Pb with a density of 11.34 g/cm^3 (dashed line), and W with a density of 19.30 g/cm^3 (dotted line). The filled squares are measured data.

observed that the off-axis factor decreases by 6% at 15 cm radius (see Fig. 4.8).

4.2.9 Sensitivity to the electron beam angle of incidence

If the angle of a parallel beam of electrons incident from vacuum is changed from 0.0° to 0.5° , it is observed that the entire shape of the off-axis factor plot is changed (see Fig. 4.9). The off-axis factors in the oblique case are higher, up to a radius of about 12 cm, by more than 1%, but lower by about 4% at 15 cm, compared to normal incidence. Of course Fig. 4.9 does not represent the variation of measured off-axis factors, if the angle of incidence of the electron beam is changed in reality. The reason is that the calculated off-axis factors assume cylindrical symmetry and are scored in concentric annular regions around the central axis of the linac. The goal of this sensitivity study is just to show that off-axis factors, even the way they are calculated in this work, are very sensitive to the angle of incidence of the electron beam on the target.

4.2.10 Sensitivity to target lateral dimensions

Some manufacturers claim that the target's lateral dimensions assumed in the simulations, have no effect on the calculated off-axis factors. The statement is primarily made to avoid revealing proprietary details of target construction. The statement is only true if the target width is much larger than the lateral spread of electrons in the target or the radius of the upstream opening of the primary collimator. In the latter case, when the target's width is cut too short, one misses scattered photons from within it and the calculated off-axis factors are reduced substantially (see Fig. 4.10).

Figure 4.8: The sensitivity of off-axis factors to the density of the flattening filter, 19.3 g/cm^3 (solid line), 18 g/cm^3 (dashed line), 17 g/cm^3 (dotted line). The density of the flattening filter should be known to better than 0.1 g/cm^3 . The filled squares are measured data.

Figure 4.9: The sensitivity of the calculated off-axis factors to the angle of incidence of the electron beam on the target. Normal incidence (solid line), incidence at 0.5° to normal (dashed line). Note that the calculated off-axis factor for an incidence of 0.5° would not represent measured values under the same condition, since the calculations are based on the assumption of cylindrical symmetry of the emitted photon beam with respect to the central axis. The filled squares are measured data.

Figure 4.10: The sensitivity of the off-axis factor to the lateral dimensions of the target. The calculations are done for targets with lateral width values of 20 cm (thick solid line), 3.2 cm (dashed line), 2.0 cm (dotted line), 1.0 cm (dash-dotted line), and 0.4 cm (thin solid line). The primary collimator upper opening has a radius of 1.75 cm and is located at a distance of 1.6 cm away from the upstream surface of the target. Note that in this study the off-axis factors are not matched to measurements.

4.2.11 Off-axis factors for all the beams studied

For all the beams studied here, Fig. 4.11 shows a comparison between measurements and off-axis factors calculated using the parameters specified in table 4.1 on page 92. The calculated off-axis factors, for all beams studied, match those compiled by TG-46,¹¹⁵ within statistical uncertainties (2σ level). The calculated uncertainties are typically 1%, at the 1σ level. The statistical uncertainties of measured off-axis factors vary dramatically, since the number of data sets used in the report for different beams is different.

4.3 Matching central-axis depth-ionization

As discussed above, matching off-axis factors alone does not lead to a uniquely specified beam energy. This is true since in addition to the electron beam energy, the electron beam intensity distribution incident on the target also influences the off-axis factor dramatically, and (just like the beam energy) it is only nominally specified by the manufacturer (see table 4.1).

Both off-axis factors and relative depth-dose values are used to specify the beams, in the comparisons of calculations with measurements. The advantage of starting with off-axis factors, when searching for the right electron beam energy, is that one only needs to simulate the linac, unlike relative depth-dose calculations where a second (phantom) simulation is also necessary. However, the advantage of comparing relative depth-dose values is that they are strongly related to the electron beam energy and not its radial intensity distribution.

Figures 4.12 - 4.20 show comparisons of the simulated relative depth-dose distributions with measurements. All data are normalized to the value of dose at 10 cm depth ($dd(10)$), which is obtained from a 4-th order polynomial fit to the fall-off region of the depth-dose curve on the central axis. The fit starts at about 2 cm past

Figure 4.11: Comparison of the calculated (solid lines) and measured (squares) (from TG-46¹¹⁵) in-air off-axis factors for the commercial linacs studied in this work.

depth of maximum dose and runs down to a depth of about 21 cm. The use of the fit eliminates the need for the calculations and measurements to have similar binings, or as a minimum, to have a bin centered at the normalization point (10 cm depth). An alternative method of normalization would be to simply normalize the curves to maximum dose, but due to the relatively large statistical noise around depth of maximum dose, that method is not adopted in this work. The calculated depth-dose values are not converted to depth-ionization, since, as discussed in section 3.2.3.3 on page 63, the variation of $(\bar{L}/\rho)_{\text{air}}^{\text{water}}$ with depth makes only a small change in the shape of the depth-dose curve. To provide a more sensitive tool to compare calculated and measured depth-dose values, difference plots as shown by the upper-right insets in Figs. 4.12 - 4.20 are used. The calculated and measured data agree within 1% (local dose), for statistics of about 1% (1σ level), at all depths past depth of maximum dose for all beams, except the 6 MV beam from Varian, where the agreement is worse at larger depths but it is still better than 2.5% of the local dose and much less than 1% of maximum dose. If the energy spread of the electron beam in the 6 MV beam of the Varian linac is increased from 3% to 17%, this discrepancy at larger depths is reduced. The agreement in the build-up region, for those beams for which measured data in this region were available, has not been as good as the fall-off region of the relative depth-dose curve. No attempt is made to improve the agreement in the build-up region, since the conditions under which the measurements were performed in this region (and whether or not they were corrected for the effective point of measurement (see section 3.2.2.2 on page 56, for example) are not specified by TG-46¹¹⁵ documentation.

Figures 4.12 - 4.20 furthermore show the contribution to dose from contaminant electrons (solid lines). This contribution is depicted as the percentage of maximum dose in the lower-left insets in Figs. 4.12 - 4.20. The lower-left insets also specify the location of depth of maximum dose (vertical solid lines). The depth-dose characteristics of the beams studied in this work are summarized in table 4.2.

The report of the AAPM's task group 51 (TG-51)¹²⁷ provides a recipe to calculate the percentage depth-dose at 10 cm for a photon-only beam [%dd_x(10)] from the value of percentage depth-dose in an actual beam [%dd(10)] (*i.e.*, one which also has electron contamination) using the formula proposed by Rogers¹²⁸ (for %dd(10) greater than 75):

$$\%dd_x(10) = 1.2667 (\%dd(10)) - 20.0 \quad (4.3)$$

The following observations are made based on the calculations of this work: firstly, %dd_x(10) = %dd(10) within better than 0.7%, for the 4, 6 and 10 MV beams, in agreement with TG-51,¹²⁷ secondly the calculated values of %dd_x(10) for the higher-energy beams differs in some cases from those obtained from Eq. 4.3. The % differences [(TG51–here)/TG51] in the calculated values of %dd_x(10) are as follows: -1.5% (for the 15 MV beam), -0.3% (for Siemens KD 18 MV beam), -0.75% (for Varian 18 MV beam), and -1.6% (for Philips 25 MV beam). In all cases the simple formula over-estimates the effect of electron contamination, however it is always within the 2% accuracy claimed.

4.4 Comparison of photon spectra with Mohan *et al.*'s

Figure 4.21 compares photon spectra (number of photons per MeV per incident electron on the target) obtained in this work, for all the beams studied, with spectra (number of photons per MeV) published by Mohan *et al.*¹ Each one of Mohan's spectra is normalized to the peak of the corresponding spectrum calculated in this work. The Varian machines used in the two studies are similar yet different. There are small differences in the thickness of the target and its backing but only for the 4 and 6 MV beams. Also, the material of the flattening filters used in the two studies are different at 6 and 10 MV. Differences in the average photon energies are discussed in the next

Figure 4.12: Comparison of the calculated (using a 0.1 cm FWHM, 3.8 MeV electron beam with 3% spread) (∇) and measured ($\blacktriangle$) central-axis depth dose data for the 4 MV photon beam of the Varian low-energy accelerator. The upper-right inset shows the local difference (calc-meas) between the calculations and measurements in percent. Where no measured data are available, the difference is assigned a value of zero with zero size error bars. The lower-left inset shows the electron contamination (also shown as the solid line in the main panel) around depth of maximum dose (shown by the vertical line). Also shown are the values for $\%dd$ at 10 cm depth for both curves.

Figure 4.13: Comparison of the calculated (using a 0.15 cm FWHM, 6.0 MeV electron beam with 3% spread) ($\blacktriangledown$) and measured ($\blacktriangle$) central-axis depth dose data for the 6 MV photon beam of the Varian high-energy accelerator. The upper-right inset shows the local difference (calc-meas) between the calculations and measurements in percent. The lower-left inset shows the electron contamination (also shown as the solid line in the main panel) around depth of maximum dose (shown by the vertical line). Also shown are the values for %dd at 10 cm depth for both curves.

Figure 4.14: Comparison of the calculated (using a 0.4 cm FWHM, 6.5 MeV electron beam with 14% spread) ($\blacktriangledown$) and measured ($\blacktriangle$) central-axis depth dose data for the 6 MV photon beam of the Siemens KD accelerator. The upper-right inset shows the local difference (calc–meas) between the calculations and measurements in percent. The lower-left inset shows the electron contamination (also shown as the solid line in the main panel) around depth of maximum dose (shown by the vertical line). Also shown are the values for % dd at 10 cm depth for both curves.

Figure 4.15: Comparison of the calculated (using a 0.1 cm FWHM, 6.2 MeV electron beam with 17% spread) ($\blacktriangledown$) and measured ($\blacktriangle$) central-axis depth dose data for the 6 MV photon beam of the Philips SL25 6 MV accelerator. The upper-right inset shows the local difference (calc-meas) between the calculations and measurements in percent. The lower-left inset shows the electron contamination (also shown as the solid line in the main panel) around depth of maximum dose (shown by the vertical line). Also shown are the values for % dd at 10 cm depth for both curves. Measured data are from Palta *et al.*¹¹⁶

Figure 4.16: Comparison of the calculated (using a 0.15 cm FWHM, 10.5 MeV electron beam with 3% spread) ($\blacktriangledown$) and measured ($\blacktriangle$) central-axis depth dose data for the 10 MV photon beam of the Varian high-energy accelerator. The upper-right inset shows the local difference (calc–meas) between the calculations and measurements in percent. The lower-left inset shows the electron contamination (also shown as the solid line in the main panel) around depth of maximum dose (shown by the vertical line). Also shown are the values for %dd at 10 cm depth for both curves.

Figure 4.17: Comparison of the calculated (using a 0.15 cm FWHM, 14.8 MeV electron beam with 3% spread) ($\blacktriangledown$) and measured ($\blacktriangle$) central-axis depth dose data for the 15 MV photon beam of the Varian high-energy accelerator. The upper-right inset shows the local difference (calc–meas) between the calculations and measurements in percent. The lower-left inset shows the electron contamination (also shown as the solid line in the main panel) around depth of maximum dose (shown by the vertical line). Also shown are the values for %dd at 10 cm depth for both curves.

Figure 4.18: Comparison of the calculated (using a 0.2 cm FWHM, 13.5 MeV electron beam with 14% spread) ($\blacktriangledown$) and measured ($\blacktriangle$) central-axis depth dose data for the 18 MV photon beam of the Siemens KD accelerator. The upper-right inset shows the local difference (calc-meas) between the calculations and measurements in percent. The lower-left inset shows the electron contamination around depth of maximum dose (shown by the vertical line). Also shown are the values for %dd at 10 cm depth for both curves. Measured data are provided by Dr. Alf Siochi, Siemens Oncology Systems, since TG-46 lacked %dd data for this beam.

Figure 4.19: Comparison of the calculated (using a 0.11 cm FWHM, 18.3 MeV electron beam with 3% spread) (∇) and measured ($\blacktriangle$) central-axis depth dose data for the 18 MV photon beam of the Varian high-energy accelerator. The upper-right inset shows the local difference (calc-meas) between the calculations and measurements in percent. The lower-left inset shows the electron contamination (also shown as the solid line in the main panel) around depth of maximum dose (shown by the vertical line). Also shown are the values for %dd at 10 cm depth for both curves.

Figure 4.20: Comparison of the calculated (using a 0.1 cm FWHM, 18.5 MeV electron beam with 5% spread) ($\blacktriangledown$) and measured ($\blacktriangle$) central-axis depth dose data for the 25 MV photon beam of the Philips SL25 accelerator. The upper-right inset shows the local difference (calc–meas) between the calculations and measurements in percent. The lower-left inset shows the electron contamination (also shown as the solid line in the main panel) around depth of maximum dose (shown by the vertical line). Also shown are the values for %dd at 10 cm depth for both curves. Measured data are from Palta *et al.*¹¹⁶

Table 4.2: Central-axis depth-dose characteristics of the realistic photon beams studied in this work and presented in Figures 4.12 - 4.20. E_n is the nominal accelerating potential, $\%dd_x(0)$ is the percentage surface dose from photons only, $\%dd_e(0)$ is the electron contamination dose at the surface, $\%dd_e(d_{max})$ is the electron contamination dose at depth of maximum dose, $\%dd_c(10)$ is the calculated value of dose at 10 cm depth, and $\%dd_m(10)$ is the measured value of dose at 10 cm depth. The $\%dd_x(0)$ and $\%dd_e(0)$ values are averaged in the first slab which is 0.25 cm thick, whereas the value of $\%dd_e(d_{max})$ is averaged in a 0.5 cm thick slab. The $\%dd_c(10)$ and $\%dd_m(10)$ values are calculated from 4-th order polynomial fits to the fall-off region of the $\%dd$ curve. The central region is defined by a cylinder of radius 1.0 cm. The uncertainty in the depth of maximum dose (d_{max}) is 0.25 cm. The uncertainty in maximum dose (D_{max}), based on a 0.5 cm thick bin for its calculation, is estimated to be 0.7% for the 4 MV beam and 0.5% for the 25 MV beam.

linac	E_n	d_{max} (cm)	$D_{max} \times 10^{17}$ (Gy/inc. e^-)	$\%dd_x(0)$ (%)	$\%dd_e(0)$ (%)	$\%dd_e(d_{max})$ (%)	$\%dd_c(10)$ (%)	$\%dd_m(10)$ (%)
Varian Clinac LE	4	1.0	3.45 ± 0.01	50 ± 1	7.0 ± 0.7	0.20 ± 0.06	62.8 ± 0.2	63.0 ± 0.6
Varian Clinac HE	6 10 15 18	1.5 2.5 2.5 3.5	12.3 ± 0.2 29.4 ± 0.2 76.5 ± 0.5 91.6 ± 0.4	41 ± 2 25 ± 1 21 ± 1 17 ± 1	5 ± 1 6 ± 1 7.4 ± 0.6 8.9 ± 0.7	0.08 ± 0.05 0.68 ± 0.09 2.6 ± 0.2 2.5 ± 0.2	66.4 ± 0.8 74.1 ± 0.4 76.9 ± 0.4 79.8 ± 0.3	66.5 ± 0.7 73.7 ± 0.7 77.1 ± 0.8 79.7 ± 0.8
Philips SL25	6 25	1.5 3.0	11.4 ± 0.1 66.1 ± 0.7	39 ± 2 14 ± 2	7 ± 1 12 ± 1	0.3 ± 0.1 5.0 ± 0.6	67.2 ± 0.7 80.8 ± 0.8	68.0 ± 0.7 81.5 ± 0.8
Siemens KD	6 18	1.5 3.0	18.2 ± 0.1 65.0 ± 0.2	39 ± 1 19.8 ± 0.5	6 ± 1 6.8 ± 0.4	0.6 ± 0.1 1.10 ± 0.08	66.9 ± 0.5 77.3 ± 0.2	67.8 ± 0.7 77.3 ± 0.4

section. For the purpose of comparison, panels c,d, and g compare Mohan's spectra, with the spectra calculated in this work for corresponding energies but produced by linacs made by other manufacturers. Mohan's data lack an 18 MV beam, therefore panels h and i, only present the spectra calculated in this work.

4.5 Analysis of photon spectra

Figure 4.22 shows how the three 6 MV photon spectra calculated in this work compare. The ratio of Siemens and Philips 6 MV beams to that of Varian shows that the Siemens beam produces more photons per incident electron than Varian or Philips. The spectral shapes are somewhat similar. The differences at the high-energy end are caused by the differences in the mean incident electron energies and their spreads (see table 4.1 on page 92).

Figure 4.23 shows the calculated average energies at 100 cm SSD in a $10 \times 10 \text{ cm}^2$ field for all the beams studied. For comparison, values calculated by Mohan *et al.*¹ for Varian machines (in an open field) are also shown as filled circles. The average energy distributions are also decomposed to show the total (solid histograms), direct (dashed histograms) and scattered photon (dotted histograms) components. Direct photons are those which have not interacted anywhere past the target before reaching the scoring plane.

The agreement is quite good for the 4, 6, and 15 MV beams of Varian machines despite spectral differences (see Fig. 4.21). The calculated values of the average energy for the 10 MV beam do not agree with those calculated by Mohan *et al.*¹ It is evident that the 10 MV beam is higher in energy than that calculated by Mohan. However, the match obtained for both off-axis factors and relative depth-dose indicate that the energy of the electron beam incident on the target, cannot be dramatically lower than that assumed in this work (*i.e.*, 10.5 MeV). Mohan's calculated TMRs¹ dramatically underestimate measured values at 10 MV, supporting the fact that the

Figure 4.21: Comparison of the photon spectra calculated here (histograms) with those previously published by Mohan *et al.*¹ (filled circles) for Varian machines. Each one of Mohan's spectra is normalized to the peak of the corresponding spectrum calculated in this work. The circles are for the region $0 \leq r \leq 3$ cm, and the histograms correspond to $0 \leq r \leq 2.25$ cm. Panel g shows a comparison of the 25 MV beam of a Philips SL25 machine with a 24 MV beam of a Varian machine. Since Mohan *et al.* had no 18 MV beam, no comparison is made at this energy. The spectra are tabulated in tables 4.3, 4.4, and 4.5.

Table 4.3: Photon fluence spectra (photons per MeV per incident electron) of the 15-25 MV beams, as shown in Fig. 4.21 for the radial bin $0 \leq r \leq 2.25$ cm. The bins are 250 keV wide, and the fluence data are tabulated with the energy at center of each bin. The percentage uncertainty in each bin is presented in parentheses. The spectra are continued in table 4.4.

E (MeV)	Philips (25 MV)	Varian (18 MV)	Siemens (18 MV)	Varian (15 MV)
0.125	0.238E-04(6.2%)	0.246E-04(3.5%)	0.257E-04(2.7%)	0.374E-05(9.5%)
0.375	0.552E-04(4.3%)	0.564E-04(2.3%)	0.121E-03(1.1%)	0.330E-04(2.9%)
0.625	0.795E-04(3.4%)	0.126E-03(1.3%)	0.179E-03(0.9%)	0.155E-03(1.2%)
0.875	0.770E-04(3.1%)	0.168E-03(1.1%)	0.185E-03(0.8%)	0.237E-03(0.9%)
1.125	0.970E-04(2.8%)	0.204E-03(1.0%)	0.190E-03(0.8%)	0.281E-03(0.8%)
1.375	0.107E-03(2.5%)	0.216E-03(0.9%)	0.185E-03(0.8%)	0.280E-03(0.8%)
1.625	0.101E-03(2.3%)	0.219E-03(0.9%)	0.179E-03(0.8%)	0.274E-03(0.8%)
1.875	0.104E-03(2.2%)	0.211E-03(0.9%)	0.169E-03(0.8%)	0.256E-03(0.8%)
2.125	0.111E-03(2.2%)	0.205E-03(0.9%)	0.160E-03(0.8%)	0.232E-03(0.9%)
2.375	0.105E-03(2.2%)	0.195E-03(0.9%)	0.149E-03(0.8%)	0.215E-03(0.9%)
2.625	0.103E-03(2.2%)	0.184E-03(0.9%)	0.141E-03(0.8%)	0.192E-03(0.9%)
2.875	0.992E-04(2.1%)	0.172E-03(1.0%)	0.131E-03(0.8%)	0.177E-03(0.9%)
3.125	0.975E-04(2.1%)	0.162E-03(1.0%)	0.125E-03(0.8%)	0.160E-03(1.0%)
3.375	0.936E-04(2.1%)	0.151E-03(1.0%)	0.114E-03(0.8%)	0.148E-03(1.0%)
3.625	0.869E-04(2.2%)	0.142E-03(1.0%)	0.107E-03(0.8%)	0.135E-03(1.1%)
3.875	0.851E-04(2.1%)	0.130E-03(1.0%)	0.101E-03(0.9%)	0.123E-03(1.1%)
4.125	0.841E-04(2.2%)	0.125E-03(1.1%)	0.949E-04(0.9%)	0.113E-03(1.1%)
4.375	0.778E-04(2.3%)	0.114E-03(1.1%)	0.897E-04(0.9%)	0.103E-03(1.1%)
4.625	0.724E-04(2.0%)	0.108E-03(1.1%)	0.830E-04(0.9%)	0.937E-04(1.2%)
4.875	0.741E-04(2.2%)	0.101E-03(1.1%)	0.774E-04(0.9%)	0.891E-04(1.2%)
5.125	0.691E-04(2.2%)	0.955E-04(1.2%)	0.734E-04(1.0%)	0.824E-04(1.3%)
5.375	0.639E-04(2.3%)	0.899E-04(1.2%)	0.697E-04(1.0%)	0.764E-04(1.3%)
5.625	0.609E-04(2.2%)	0.853E-04(1.2%)	0.650E-04(1.0%)	0.722E-04(1.3%)
5.875	0.582E-04(2.3%)	0.804E-04(1.2%)	0.620E-04(1.0%)	0.660E-04(1.4%)
6.125	0.550E-04(2.2%)	0.744E-04(1.3%)	0.574E-04(1.0%)	0.619E-04(1.4%)
6.375	0.507E-04(2.3%)	0.710E-04(1.3%)	0.555E-04(1.1%)	0.566E-04(1.5%)
6.625	0.473E-04(2.2%)	0.669E-04(1.4%)	0.530E-04(1.1%)	0.533E-04(1.5%)
6.875	0.465E-04(2.3%)	0.627E-04(1.4%)	0.492E-04(1.1%)	0.496E-04(1.5%)
7.125	0.463E-04(2.2%)	0.605E-04(1.5%)	0.462E-04(1.1%)	0.483E-04(1.5%)
7.375	0.424E-04(2.5%)	0.561E-04(1.5%)	0.448E-04(1.1%)	0.448E-04(1.7%)
7.625	0.423E-04(2.3%)	0.535E-04(1.5%)	0.420E-04(1.2%)	0.413E-04(1.7%)
7.875	0.398E-04(2.4%)	0.500E-04(1.5%)	0.405E-04(1.2%)	0.399E-04(1.7%)
8.125	0.368E-04(2.5%)	0.486E-04(1.6%)	0.380E-04(1.2%)	0.366E-04(1.8%)
8.375	0.371E-04(2.7%)	0.448E-04(1.6%)	0.363E-04(1.3%)	0.351E-04(1.8%)
8.625	0.351E-04(2.7%)	0.429E-04(1.7%)	0.337E-04(1.3%)	0.332E-04(1.9%)
cont ...	cont ...	cont ...	cont ...	cont ...

Table 4.4: Continuation of table 4.3.

E (MeV)	Philips (25 MV)	Varian (18 MV)	Siemens (18 MV)	Varian (15 MV)
8.875	0.328E-04(2.7%)	0.401E-04(1.7%)	0.322E-04(1.3%)	0.299E-04(2.0%)
9.125	0.320E-04(2.8%)	0.384E-04(1.7%)	0.311E-04(1.4%)	0.288E-04(2.0%)
9.375	0.298E-04(2.8%)	0.386E-04(1.7%)	0.291E-04(1.4%)	0.276E-04(2.0%)
9.625	0.296E-04(2.7%)	0.347E-04(1.8%)	0.274E-04(1.4%)	0.261E-04(2.1%)
9.875	0.286E-04(2.8%)	0.341E-04(1.8%)	0.260E-04(1.5%)	0.244E-04(2.1%)
10.125	0.287E-04(2.7%)	0.322E-04(1.9%)	0.244E-04(1.5%)	0.230E-04(2.3%)
10.375	0.263E-04(3.3%)	0.302E-04(1.9%)	0.224E-04(1.6%)	0.220E-04(2.2%)
10.625	0.256E-04(3.0%)	0.292E-04(1.9%)	0.211E-04(1.6%)	0.207E-04(2.3%)
10.875	0.240E-04(3.1%)	0.286E-04(1.9%)	0.199E-04(1.7%)	0.188E-04(2.4%)
11.125	0.242E-04(3.0%)	0.259E-04(2.0%)	0.180E-04(1.8%)	0.179E-04(2.4%)
11.375	0.212E-04(3.2%)	0.253E-04(2.1%)	0.162E-04(1.8%)	0.171E-04(2.5%)
11.625	0.218E-04(3.1%)	0.242E-04(2.1%)	0.162E-04(1.8%)	0.150E-04(2.8%)
11.875	0.205E-04(3.2%)	0.239E-04(2.2%)	0.135E-04(2.0%)	0.148E-04(2.7%)
12.125	0.198E-04(3.6%)	0.228E-04(2.1%)	0.120E-04(2.2%)	0.144E-04(2.7%)
12.375	0.196E-04(3.4%)	0.224E-04(2.3%)	0.968E-05(2.3%)	0.130E-04(3.0%)
12.625	0.192E-04(3.6%)	0.204E-04(2.3%)	0.856E-05(2.6%)	0.111E-04(3.1%)
12.875	0.174E-04(3.5%)	0.199E-04(2.3%)	0.692E-05(2.8%)	0.105E-04(3.1%)
13.125	0.170E-04(3.5%)	0.190E-04(2.3%)	0.551E-05(3.1%)	0.906E-05(3.6%)
13.375	0.162E-04(3.8%)	0.177E-04(2.4%)	0.371E-05(3.7%)	0.822E-05(3.5%)
13.625	0.160E-04(3.7%)	0.166E-04(2.6%)	0.284E-05(4.3%)	0.721E-05(3.8%)
13.875	0.139E-04(3.9%)	0.156E-04(2.6%)	0.161E-05(5.6%)	0.552E-05(4.3%)
14.125	0.138E-04(4.4%)	0.151E-04(2.6%)	0.993E-06(7.2%)	0.471E-05(4.7%)
14.375	0.130E-04(4.0%)	0.148E-04(2.6%)	0.604E-06(9.2%)	0.314E-05(5.7%)
14.625	0.125E-04(4.1%)	0.138E-04(2.8%)	0.332E-06(12.4%)	0.158E-05(8.1%)
14.875	0.121E-04(4.2%)	0.121E-04(2.9%)	0.163E-06(17.7%)	0.510E-06(14.3%)
15.125	0.115E-04(4.3%)	0.124E-04(2.9%)	0.914E-07(23.6%)	0.625E-07(40.8%)
15.375	0.107E-04(4.4%)	0.111E-04(3.3%)	0.355E-07(37.8%)	
15.625	0.958E-05(4.7%)	0.109E-04(3.1%)	0.204E-07(50.0%)	
15.875	0.930E-05(4.7%)	0.102E-04(3.2%)		
16.125	0.823E-05(5.0%)	0.896E-05(3.4%)		
16.375	0.812E-05(5.2%)	0.795E-05(3.6%)		
16.625	0.806E-05(5.1%)	0.734E-05(3.7%)		
16.875	0.668E-05(5.6%)	0.702E-05(3.8%)		
17.125	0.532E-05(6.3%)	0.571E-05(4.2%)		
17.375	0.471E-05(6.7%)	0.467E-05(4.7%)		
17.625	0.392E-05(7.3%)	0.375E-05(5.2%)		
17.875	0.304E-05(8.3%)	0.222E-05(6.8%)		
18.125	0.210E-05(10.0%)	0.130E-05(8.8%)		
18.375	0.112E-05(13.6%)	0.356E-06(16.9%)		
18.625	0.603E-06(18.6%)	0.509E-07(44.7%)		
18.875	0.270E-06(27.7%)			
19.125	0.621E-07(57.7%)			

Table 4.5: 4-10 MV photon fluence spectra (photons per MeV per incident electron), for the radial bin $0 \leq r \leq 2.25$ cm, as shown in Fig. 4.21. The bins are 250 keV wide, and the fluence data are tabulated with the energy at center of each bin. The uncertainty in each bin is presented in parentheses.

E (MeV)	Varian (10 MV)	Varian (6 MV)	Siemens (6 MV)	Philips (6 MV)	Varian (4 MV)
0.125	0.185E-04(2.8%)	0.229E-04(4.1%)	0.436E-04(1.6%)	0.223E-04(3.7%)	0.923E-07(19.4%)
0.375	0.866E-04(1.2%)	0.135E-03(1.5%)	0.216E-03(0.6%)	0.119E-03(1.4%)	0.173E-04(1.2%)
0.625	0.114E-03(1.0%)	0.147E-03(1.4%)	0.210E-03(0.6%)	0.127E-03(1.3%)	0.532E-04(0.6%)
0.875	0.116E-03(1.0%)	0.125E-03(1.5%)	0.175E-03(0.6%)	0.109E-03(1.3%)	0.570E-04(0.6%)
1.125	0.114E-03(0.9%)	0.108E-03(1.5%)	0.149E-03(0.6%)	0.922E-04(1.3%)	0.507E-04(0.6%)
1.375	0.108E-03(0.9%)	0.945E-04(1.6%)	0.127E-03(0.7%)	0.803E-04(1.3%)	0.414E-04(0.7%)
1.625	0.104E-03(1.0%)	0.814E-04(1.8%)	0.110E-03(0.7%)	0.697E-04(1.3%)	0.333E-04(0.7%)
1.875	0.962E-04(1.0%)	0.717E-04(1.8%)	0.941E-04(0.8%)	0.606E-04(1.4%)	0.269E-04(0.8%)
2.125	0.889E-04(1.0%)	0.616E-04(2.0%)	0.820E-04(0.8%)	0.521E-04(1.4%)	0.214E-04(0.9%)
2.375	0.844E-04(1.0%)	0.528E-04(2.1%)	0.724E-04(0.8%)	0.462E-04(1.5%)	0.167E-04(1.0%)
2.625	0.764E-04(1.1%)	0.458E-04(2.0%)	0.628E-04(0.9%)	0.405E-04(1.6%)	0.130E-04(1.1%)
2.875	0.710E-04(1.1%)	0.389E-04(2.2%)	0.553E-04(0.9%)	0.364E-04(1.6%)	0.973E-05(1.2%)
3.125	0.651E-04(1.1%)	0.351E-04(2.4%)	0.482E-04(1.0%)	0.327E-04(1.7%)	0.723E-05(1.4%)
3.375	0.587E-04(1.1%)	0.308E-04(2.5%)	0.426E-04(1.0%)	0.275E-04(1.8%)	0.465E-05(1.6%)
3.625	0.556E-04(1.2%)	0.266E-04(2.7%)	0.375E-04(1.1%)	0.259E-04(1.9%)	0.220E-05(2.3%)
3.875	0.507E-04(1.2%)	0.234E-04(2.8%)	0.339E-04(1.2%)	0.219E-04(2.0%)	0.173E-06(7.2%)
4.125	0.474E-04(1.2%)	0.188E-04(2.9%)	0.289E-04(1.2%)	0.200E-04(2.1%)	
4.375	0.440E-04(1.3%)	0.174E-04(3.0%)	0.258E-04(1.3%)	0.168E-04(2.3%)	
4.625	0.400E-04(1.3%)	0.145E-04(3.4%)	0.230E-04(1.3%)	0.152E-04(2.4%)	
4.875	0.371E-04(1.3%)	0.123E-04(3.7%)	0.197E-04(1.4%)	0.128E-04(2.4%)	
5.125	0.353E-04(1.4%)	0.968E-05(4.2%)	0.165E-04(1.5%)	0.102E-04(2.7%)	
5.375	0.322E-04(1.4%)	0.706E-05(5.0%)	0.138E-04(1.6%)	0.812E-05(3.1%)	
5.625	0.301E-04(1.5%)	0.459E-05(5.5%)	0.111E-04(1.8%)	0.615E-05(3.3%)	
5.875	0.278E-04(1.5%)	0.202E-05(7.8%)	0.847E-05(2.0%)	0.425E-05(3.7%)	
6.125	0.259E-04(1.5%)	0.162E-06(27.8%)	0.572E-05(2.4%)	0.253E-05(4.8%)	
6.375	0.237E-04(1.6%)		0.313E-05(3.3%)	0.133E-05(8.0%)	
6.625	0.223E-04(1.7%)		0.150E-05(4.3%)	0.548E-06(10.3%)	
6.875	0.204E-04(1.7%)		0.570E-06(8.1%)	0.181E-06(17.2%)	
7.125	0.190E-04(1.8%)		0.120E-06(14.9%)	0.524E-07(31.6%)	
7.375	0.173E-04(1.9%)		0.183E-07(37.8%)		
7.625	0.162E-04(1.9%)				
7.875	0.146E-04(2.0%)				
8.125	0.134E-04(2.1%)				
8.375	0.123E-04(2.1%)				
8.625	0.106E-04(2.2%)				
8.875	0.949E-05(2.5%)				
9.125	0.815E-05(2.6%)				
9.375	0.674E-05(2.8%)				
9.625	0.563E-05(3.1%)				
9.875	0.419E-05(3.5%)				
10.125	0.275E-05(4.3%)				
10.375	0.115E-05(6.7%)				
10.625	0.171E-06(17.4%)

Figure 4.22: Ratio of photon spectra of Siemens and Philips 6 MV beams to that of Varian.

incident energy assumed by them is lower than it should be. Panels b, e, and f, show an intercomparison of average energies for the same nominal accelerating potential (6 MV) produced by the three different manufacturers. It can be seen that the calculated average energies of the photon beams produced by the three linacs are very close. Since Mohan's calculations lack an 18 MV beam, panels g and h, show no comparisons at this energy. Finally, panel i, compares a Philips SL25 25 MV photon beam with a 24 MV beam calculated by Mohan for a Varian machine.

Figures 4.24, 4.25 and 4.26 show the energy weighted photon spectra over a $10 \times 10 \text{ cm}^2$ field, as opposed to the central axis spectra shown in Fig. 4.21, for all the beams studied in this work. For most of the beams, 94-97% of the photons are direct (*i.e.*, they have only interacted in the target, before reaching the scoring plane at 100 cm). The Philips 25 MV beam has the largest amount of scattered photons, resulting in about 90% direct photons. The scattered photons are grouped in three major categories: those last scattered from the primary collimator, the flattening filter-, and the field defining jaws. Most of the scattered photons appear to originate from (*i.e.*, they scatter for the last time in) the primary collimator or the flattening filter. In some of the beams, a flattening filter is embedded in the conical opening of the primary collimator, making the distinction between the flattening filter and the primary collimator difficult as far as the actual source for scattered photons is concerned. To simplify this, the ZLAST feature of the BEAM code is used, whereby the primary collimator is (conceptually) divided into two components: one containing a flattening filter (for those beams which do have an embedded flattening filter inside the primary collimator) and one which doesn't (usually the top part of the primary collimator). The division is performed by a plane perpendicular to the central axis. As a result, if a photon scatters (for the last time before reaching the scoring plane) in the primary collimator, above the dividing plane but inside the primary collimator, then it is taken as a primary collimator-scattered photon, and if it is scattered anywhere below the dividing plane (inside the primary collimator or inside the em-

Figure 4.23: Calculated average (above 0.01 MeV) photon energies at 100 cm, scored in annular bins, for the commercial linacs studied in this work. The filled circles are calculated by Mohan *et al.*¹ for Varian Clinacs (open field). The three histograms represent average energies for: all photons (solid histograms), direct photons (dashed histograms), and scattered photons (dotted histograms). The vertical dashed lines represent the half-width and the half-diagonal of the field.

Figure 4.24: Photon energy fluence spectra, averaged over a $10 \times 10 \text{ cm}^2$ field. The bin size is 250 keV. The values printed on the lower left of each panel represent the contributions to the energy fluence in percentage from (top to bottom): direct photons (thick solid histogram), photons last scattered in the primary collimator (dashed histogram), photons last scattered in the flattening filter (dotted), and photons last scattered in the jaws (thin solid). Histograms representing total photons are also plotted, which can be distinguished from direct photons only in the high-energy beams. The contributions to photon energy fluence are summarized in table 4.6.

Figure 4.25: Photon energy fluence spectra, averaged over a $10 \times 10 \text{ cm}^2$ field. The bin size is 250 keV. The values printed on the lower left of each panel represent the contributions to the energy fluence in percentage from (top to bottom): direct photons (thick solid histogram), photons last scattered in the primary collimator (dashed histogram), photons last scattered in the flattening filter (dotted), and photons last scattered in the jaws (thin solid). Histograms representing total photons are also plotted, which can be distinguished from direct photons only in the high-energy beams. The contributions to photon energy fluence are summarized in table 4.6.

Figure 4.26: Photon energy fluence spectra, averaged over a $10 \times 10 \text{ cm}^2$ field. The bin size is 250 keV. The values printed on the lower left of each panel represent the contributions to the energy fluence in percentage from (top to bottom): direct photons (thick solid histogram), photons last scattered in the primary collimator (dashed histogram), photons last scattered in the flattening filter (dotted), and photons last scattered in the jaws (thin solid). Histograms representing total photons are also plotted, which can be distinguished from direct photons only in the high-energy beams. The contributions to photon energy fluence are summarized in table 4.6.

bedded flattening filter therein) then it's taken as a flattening filter-scattered photon. The scatter contributions from the primary collimator and the flattening filter are typically between 1-4% each. The jaws contribute a maximum of 1% in the 10×10 cm² fields studied. There may be other structures, besides the target, the primary collimator, the flattening filter and the jaws, which the beam passes through and may interact with. The scatter from those additional structures is generally much less than 1% in total, and is not depicted in Figures 4.24-4.26 or table 4.6.

4.6 Summary and conclusions

In this chapter the BEAM code, which was optimized in chapter 2 and benchmarked in chapter 3, was used to simulate real commercial medical linacs. The following summarizes the findings of this chapter.

The electron beam radial intensity distribution (or its FWHM) influences the off-axis factors to a great extent. Generally speaking, the larger the FWHM, the relatively more intense the photon beam on the central axis. The central-axis relative depth-dose values, on the other hand, are quite insensitive to such variations in the electron beam intensity distribution.

No correlation is observed between the off-axis factors and the electron beam energy spread. However, the relative depth-dose values show some sensitivity to the electron beam energy spread, especially at larger depths.

The divergence of the electron beam incident on the target in commercial linacs is ignored in the simulations of chapter 4, because in chapter 3, it is shown to have little impact on the results and there is no evidence in the available data that it is needed.

The calculated off-axis factors, for all beams studied, match those compiled by TG-46,¹¹⁵ within statistical uncertainties (at the 2σ level).

Table 4.6: Contribution of direct and scattered photons to the photon energy fluence, ψ_x , in the different beams. The values are averaged in a $10 \times 10 \text{ cm}^2$ field and the corresponding spectra, differential in energy, are plotted in Figures 4.24-4.26. PC represents the part of the primary collimator which does not include a flattening filter and FF represents the flattening filter and that part of the primary collimator which encloses it.

linac	E_n	photon per 10^6 inc e^-	direct ψ_x (%)	ψ_x from PC (%)	ψ_x from FF (%)	ψ_x from JAWS (%)
Varian Clinac LE	4	557 ± 1	95.9 ± 0.1	1.93 ± 0.02	1.86 ± 0.01	0.171 ± 0.004
Varian Clinac HE	6	1888 ± 4	95.2 ± 0.3	1.94 ± 0.05	2.58 ± 0.04	0.20 ± 0.01
	10	2932 ± 3	94.6 ± 0.1	1.11 ± 0.02	4.00 ± 0.02	0.229 ± 0.005
	15	7113 ± 5	96.2 ± 0.1	1.12 ± 0.02	2.41 ± 0.01	0.225 ± 0.004
	18	7496 ± 5	94.6 ± 0.1	0.80 ± 0.01	4.31 ± 0.02	0.220 ± 0.004
Philips SL25	6	1668 ± 3	95.6 ± 0.2	0.92 ± 0.02	2.42 ± 0.03	1.06 ± 0.02
	25	4847 ± 7	90.6 ± 0.2	3.62 ± 0.04	4.85 ± 0.03	0.90 ± 0.1
Siemens KD	6	2538 ± 2	96.9 ± 0.1	1.16 ± 0.02	0.670 ± 0.007	0.286 ± 0.005
	18	5795 ± 4	94.0 ± 0.1	1.81 ± 0.01	3.88 ± 0.02	0.284 ± 0.004

The calculated and measured depth-dose data agree within 1% (local dose), for 1% (1σ level) statistics, at all depths past depth of maximum dose for all beams, except for the 6 MV Varian beam, where the agreement is worse at larger depths but it is still better than 2.5% of the local dose. The difference method used in this chapter (see insets of Figs. 4.12 - 4.20) enhances the sensitivity of a relative depth-dose comparison appreciably. Using this method, the energy of the electron beam can be determined to about ± 0.3 MeV when the uncertainty in dose at each point is about 1% (1σ).

In one case, the derived mean electron energy incident on the target is 15% different from that specified by the manufacturer, but typically the difference is of the order of 5%. The electron energy spread is taken exactly as specified by the manufacturers, since neither the off-axis factors nor the relative depth-dose values provide a sensitive enough tool to investigate changes in the electron energy spread. The FWHM of the electron radial intensity distributions are usually larger than those specified by the manufacturers (see table 4.1 on page 92).

At 6 MV, a cross comparison between three different linacs was possible. The spectral shapes are somewhat similar. The differences at the high-energy end are caused by the differences in the mean incident electron energies and their spreads (see table 4.1). The Siemens 6 MV beam contains more low- and high-energy photons than the other two beams. Nonetheless, the calculated average energies of the photon beams produced by the three linacs are very close.

Comparison of the calculated spectra for Varian machines with those published by Mohan *et al.*¹ shows many differences. Despite spectral differences, the calculated average energies compare well for the 4, 6, and 15 MV beams of Varian machines. But the calculated values of the average energy for the 10 MV beam are significantly higher than those calculated by Mohan *et al.*¹ However, the match obtained for both off-axis factors and relative depth-dose indicate that the energy of the electron beam incident on the target cannot be dramatically lower than that assumed in this

work (*i.e.*, 10.5 MeV). Mohan *et al.*'s calculated TMRs¹ dramatically underestimate measured values at 10 MV, supporting the fact that the incident energy assumed by them is lower than it should be.

For most of the beams, 94-97% of the photons are direct (*i.e.*, they have only interacted in the target, before reaching the scoring plane at 100 cm). The Philips 25 MV beam has the highest number of scattered photons, resulting in about 90% direct photons. The scatter contributions from the primary collimator and the flattening filter are typically between 1-4% each. The jaws contribute a maximum of 1% in the $10 \times 10 \text{ cm}^2$ fields studied. There may be other structures, in addition to the target, the primary collimator, the flattening filter and the jaws, which the beam passes through and may interact with. The scatter from those additional structures is generally much less than 1% in total, and is not depicted in Fig. 4.24-4.26 or table 4.6.

Chapter 5

Summary and Future Work

5.1 Optimization

The optimization of the megavoltage photon beam simulations is done in two steps: firstly, unnecessary electron transport is minimized, through the use of range rejection and Russian Roulette techniques, and secondly the number of photons reaching the scoring zone per incident electron on the target is maximized by using selective bremsstrahlung splitting (SBS).

The significant contribution of this thesis is in the development of the selective bremsstrahlung splitting routine. Unlike uniform bremsstrahlung splitting, which is not sensitive to the end-points chosen in this work to assess the efficiency, the improvement in efficiency using selective bremsstrahlung splitting is somewhat dependent on the end-point. A proper statistical estimation of the efficiency was deemed to be necessary due to the introduction of selective bremsstrahlung splitting, because of a wide range of particle weights produced in the simulation. The use of these efficiency estimation methods when using uniform bremsstrahlung splitting together with Russian Roulette, showed significant flaws in them. These flaws are fixed as follows: in UBS splitting is allowed for higher-generation (bremsstrahlung and annihilation photons generated by secondary electrons) photons (only when Russian Roulette is also used), and Russian Roulette is extended to include all electrons (negatrons and positrons) set in motion by split photons.

The successful usage of selective bremsstrahlung splitting requires proper selection of its user-selected parameters: R_f , N_{max} and N_{min} . As a rule of thumb, $R_f \approx \sqrt{(w+10)^2/\pi}$, where w is the largest width of the field, provides optimal improvement in efficiency. A value of 200 is proposed as an optimum value for N_{max} for all cases studied here, provided a minimum value of 10 is chosen for N_{min} . One can, in principle, use larger values for N_{max} depending on the memory available, but accordingly one has to increase N_{min} to minimize “fat” photons. If the minimum splitting factor (N_{min}) is chosen to be 1, both of the SBS routines result in a de-

crease in efficiency. As a rule of thumb we recommend values for N_{min} between $0.05 - 0.1 \times N_{max}$.

5.2 Benchmark study

The optimized code is benchmarked in chapter 3 against accurate measurements of ionization in a water phantom, in the 10 and 20 MV photon beams of the NRC linac. Very good agreement is obtained with measured values of central-axis depth-ionization and ionization profiles at 3 depths. Calculation of ionization using the Monte Carlo technique required a special code (SPRXYZ) which was developed to calculate stopping-power ratios in cartesian voxels for realistic photon and electron beams.

The very accurate central-axis depth-ionization comparison suggests that the effective point of measurement of the ion chamber is 0.6 times its inner radius upstream of its centre, in contrast to the previously suggested⁹⁹ value of 0.75 times its inner radius, and in agreement with the new recommendations of IAEA.¹¹⁴

A fair amount of work was dedicated to understand the parameters influencing the shape of the penumbra in the ionization profiles. Lack of knowledge about the electron beam radial intensity distribution, its sweeping angle, and the exact jaw settings were shown to be important factors limiting a more accurate simulation of the ionization profiles. Nonetheless, the calculated profiles agree with the measured ones within 0.15 cm in the worst case, and typically much better than this.

5.3 Photon spectra from medical linear accelerators

The optimized and benchmarked BEAM code was used in chapter 4 to simulate “generic” versions of the major commercial linacs used in radiotherapy. An iterative method was used to find the “right” set of simulation parameters (*i.e.*, electron beam energy and radial distribution). Both off-axis factors and percentage depth-dose values were used in this process. The calculated off-axis factors, for all beams studied, matched those compiled by TG-46¹¹⁵ within statistical uncertainties (at the 2σ level). The calculated and measured depth-dose data agree within 1% (local dose), at about 1% (1σ level) statistics, at all depths past d_{max} for almost all beams. The energy of the electron beam incident on the target was determined to about ± 0.3 MeV. The electron beam radial intensity distribution was also determined to about ± 0.01 cm.

Comparison of the calculated spectra for Varian machines with those published by Mohan *et al.*¹ showed many differences. Despite spectral differences, the calculated average energies compared very well for the 4, 6, and 15 MV beams of the Varian machines. But the calculated values of the average energy for the 10 MV beam were significantly higher than those calculated by Mohan *et al.*

The contribution of scattered photons to the energy fluence spectra showed that, for most of the beams, 94-97% of the photons are direct (*i.e.*, they have only interacted in the target, before reaching the scoring plane at 100 cm).

5.4 Future work

In chapter 2, this work focused on optimizing the BEAM code, but equally important is the optimization of the dose calculation in a phantom (or patient), which probably has more clinical relevance.

The benchmark study in chapter 3 can be further improved by devising new techniques of measuring all the parameters needed in a linac simulation with high precision and accuracy. Only then one could possibly get close to the limit of testing the accuracy of the cross section data and the underlying physical assumptions used in EGS4.

There is a great deal of future work which can be done along the lines of chapter 4. For example calculating output factors, or using realistic photon beams to re-evaluate many of the quantities used in radiation dosimetry or radiotherapy, *e.g.*, stopping power ratios or the wall correction factor of an ion chamber (P_{wall}).

Appendix A

Calculation of the probability of photon emission into the treatment field

This appendix shows how the probability of photon emission into a field is calculated. This probability is used in chapter 2 by the selective bremsstrahlung splitting routines to optimize the efficiency of photon beam simulations of linacs.

The calculation is based on the assumption that the electron essentially remains on the central axis, throughout its transport inside the target. The Schiff cross section for bremsstrahlung, differential in both photon energy (k) and angle (θ_p) (formula 2BS ref.⁵⁷):

$$\begin{aligned} \frac{\partial^2 \sigma}{\partial k \partial \theta_p} &= \frac{4Z^2 r_0^2 y E_e}{137 k} \\ &\quad \left\{ \frac{16y^2 E}{(y^2 + 1)^4 E_e} - \frac{(E_e + E)^2}{(y^2 + 1)^2 E_e^2} + \left[\frac{E_e^2 + E^2}{(y^2 + 1)^2 E_e^2} - \frac{4y^2 E}{(y^2 + 1)^4 E_e} \right] \ln(M(y)) \right\}, \\ \frac{1}{M(y)} &= \left(\frac{k}{2E_e E} \right)^2 + \left(\frac{Z^{1/3}}{111(y^2 + 1)} \right)^2, \end{aligned} \quad (\text{A.1})$$

$$y = E_e \theta_p,$$

is used, where, E_e and E are the total electron energy before and after bremsstrahlung emission in units of electron rest mass, r_0 is the classical electron radius and Z is the atomic number of the element of interest, to calculate the probability of photon emission into the treatment field.

Fig. A.1 shows a schematic of the geometry used in calculating the probability of photon emission into the treatment field. Bremsstrahlung photons can be emitted in all directions by an electron, but those emitted towards the field have a higher chance of reaching the scoring plane. The electron is assumed to be located in the target on the central axis, making an angle θ_e with it. The projection of this angle into the plane normal to the central axis and located at a distance SSD, is called R_e . For a certain circular field size (R_f , which is selected by the user as a parameter to encompass the actual treatment field) and SSD, the probability depends on the electron energy, E_e , and the angle it makes with the central axis, θ_e (or equivalently R_e).

Probability of photon emission towards treatment field

Figure A.1: Schematic showing the geometry used to calculate the probability of photon emission into the treatment field. The electron is aimed at a distance R_e (not shown) away from the central axis in the patient plane (shown as the center of the concentric circles), making an angle θ_e with the central axis. The concentric circles represent the bremsstrahlung emission by this electron towards the field. The angle each circle makes with the direction of the electron is θ_p and the associated radius is R_p (not shown). $\theta_{p_{\min}}$ is the smallest angle the edge of the field makes with the direction of travel of the electron, and when the electron is aiming inside the field, as shown above, it is equal to zero. $\theta_{p_{\max}}$ is the largest angle the edge of the field makes with the direction of travel of the electron. The treatment field is approximated with a circle of radius R_f .

To geometrically calculate the probability one needs to know the angular distribution of bremsstrahlung for the energy of the emitting electron. This requires integration of Equation A.1 over all photon energies. Since this integral has no analytical solution (and to avoid numerical integration), we have taken the angular distribution $\left(\frac{d\sigma}{d\theta_p}\right)$ of emitted photons at a photon energy equal to $E_e/2$ as representative of the angular distribution of all photons. This is justified, since the angular distributions of photons of different energies are sufficiently similar (see Fig. 2.3). The probability of photon emission into the treatment field of radius R_f at a source to surface distance, SSD, can then be expressed as:

$$P(R_e, E_e, R_f, SSD) = \frac{\int_{\theta_{pmin}}^{\theta_{pmax}} \frac{d\sigma}{d\theta_p} \Big|_{k=E_e/2} \cdot f(\theta_p) d\theta_p}{\int_0^\pi \frac{d\sigma}{d\theta_p} \Big|_{k=E_e/2} d\theta_p}, \quad (\text{A.2})$$

where, θ_{pmin} is zero when $R_e \leq R_f$, $R_e (= SSD \tan \theta_e)$ is the distance between the points of intersection with the scoring plane, of the central axis and of the direction of the electron at the time of bremsstrahlung (see Fig. A.1), and $\frac{d\sigma}{d\theta_p} \Big|_{k=\frac{E_e}{2}}$ is our approximation for $A \int_0^{kmax} \frac{\partial^2 \sigma}{\partial k \partial \theta_p} dk$, where A is a normalization factor. $f(\theta_p)$ is given by

$$f(\theta_p) = \begin{cases} 1. & \text{if, } R_p \leq R_f - R_e \\ \frac{1}{\pi} \cos^{-1} \left(\frac{R_e^2 - R_f^2 + R_p^2}{2R_e R_p} \right) & \text{if, } R_f - R_e < R_p < R_f + R_e \\ 0. & \text{if, } R_f + R_e \leq R_p, \end{cases} \quad (\text{A.3})$$

depicting the portion of an annulus which is enclosed by the treatment field, as shown in figure A.1, and replaces the integration over ϕ . In eq. A.3, $R_p (= SSD \tan \theta_p)$ is the projected radius (onto the scoring plane) of an annulus at angle θ_p with respect to the direction of travel of the electron at the time of bremsstrahlung.

Appendix B

Computational and statistical methods used in chapter 4

B.0.1 Distributed computing

All the off-axis factor and %dd calculations in chapter 4 are distributed over 20 Pentium Pro 200 MHz CPUs. The distributed computing is accomplished as follows: first the BEAM input file of choice is operated on, using the *pclinux* (sh+awk) script to produce multiple copies with different random number seeds. Then each copy of the input file is submitted to the NQS network queing system as an independent BEAM calculation to be run on the available Pentium computers. Each job produces a temporary directory on the local disc and outputs to that directory. At the end of the calculation, the main output of interest, viz. the phase-space file, is converted to a PAW-readable format and operated upon by PAW macro files, which output the result of this individual calculation (as well as the input file, the log file and the listing file) to a common directory on the user's disc area. The temporary directory on the machine used is then cleared of all unnecessary files. For the %dd calculations, the clearing of the temporary directory is delayed until the corresponding dose calculations are performed. The dose calculation follows automatically the linac simulation. Although the 20 sub-calculations are submitted sequentially with 20 second intervals they finish (due to the dynamic load of the computers on which they were running) in a somewhat random order. Upon completion of any of the 20 linac simulations, the presence of a flag in the linac-simulation input file triggers another script program to operate on a master copy of a pre-existing dose calculation input file and generate 20 copies with different random number seeds. The dose calculation input files are not regenerated when any of the subsequent linac sub-simulations becomes complete. In addition to setting the random number seeds, the script also specifies the location and name of the phase-space file to be read. This ensures that the dose calculation is performed on the same machine and minimizes network traffic.

B.0.2 Estimation of uncertainties

It is apparent from Eq. 4.1 that the uncertainty, s_j , associated with each OF_j results from the statistical uncertainty in each annular bin, s'_j , combined with that of the central bin s'_1 . One can calculate the relative error in the ratio $\frac{\bar{y}_j}{\bar{y}_1}$ from

$$s_j = OF_j \times \sqrt{\left(\frac{s'_j}{\bar{y}_j}\right)^2 + \left(\frac{s'_1}{\bar{y}_1}\right)^2} \quad (\text{B.1})$$

where s'_j (the standard deviation of the mean) is calculated from:

$$s'_j = \left[\frac{\sum_{i=1}^N (y_{ij} - \bar{y}_j)^2}{N(N-1)} \right]^{\frac{1}{2}} \quad (\text{B.2})$$

where

$$\bar{y}_j = \frac{\sum_{i=1}^N y_{ij}}{N}. \quad (\text{B.3})$$

and y_{ij} is the water-kerma-weighted photon fluence in the j -th annular bin calculated by the i -th CPU.

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