**Monte Carlo investigation of the influence
of ion chamber response on in-air measurements
in megavoltage photon beams**

by

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Abstract

This thesis presents an investigation of the influence of the ion chamber response on in-air off-axis ratio (OAR) profiles and head-scatter factor measurements in megavoltage photon beams using Monte Carlo (MC) simulations with the EGSnrc system. Two new techniques for the calculations of OAR profiles were developed. Results of the Monte Carlo simulations were compared with the measurements and shown to agree within the experimental and simulation uncertainties. Comparison of the OAR values with calculated air-kerma profiles demonstrates that using a plastic mini-phantom gives more accurate measurements than using high- Z material build-up caps and that the variation of chamber response, including build-up caps, with distance from the central axis must be taken into account. Head-scatter factors show about 1% difference between measurements performed with build-up caps and mini-phantom for the large field sizes. Based on the results of this investigation, the use of plastic mini-phantoms for in-air measurements is recommended.

Statement of Contribution

The methods and results of this thesis have been summarized in the paper published in *Medical Physics*, the official science journal of the American Association of Physicists in Medicine (AAPM) and an official journal of the Canadian Organization of Medical Physicists (COMP) and the Canadian College of Physicists in Medicine (CCPM). The paper has been drafted by the author who performed and analyzed all involved calculations. The simulation techniques were developed and implemented by Iwan Kawrakow and experimental data was provided by Malcolm McEwen. The results were also presented by the author at the AAPM 47th Annual Meeting in Seattle, July 24-28, 2005.

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Notation and definitions

CH	Condensed history
CM	Component modules
CPE	Charged particle equilibrium
CSDA	Continuous-slowing-down approximation
$\tilde{D}(E)$	Dose to the chamber cavity per incident photon fluence
$D(x)$	Dose to the chamber cavity when the chamber is at position x from the point source axis
DBS	Directional bremsstrahlung splitting
$d_{\max}$	Depth of the dose maximum
EGS	Electron-Gamma-Shower
$\overline{E}_o$	Mean electron energy incident on the water surface
E_a	Electron energy at the vacuum exit window of the accelerator
$(\Delta E)_{tot,n}$	Mean total energy loss in a layer n of material being traversed
$f(E, x)$	Number of photons per unit energy interval per unit solid angle
K_{air}	Kerma in air (kinetic energy released in medium)
MC	Monte Carlo
$(\mu_{\text{en}}(E)/\rho)_{\text{air}}$	Mass energy absorption coefficient in air at photon energy E
$(\mu_{\text{tr}}(E)/\rho)_{\text{air}}$	Mass energy transfer coefficient in air at photon energy E
OAR	Off-axis ratio
Φ_0	Incident photon fluence

$R(E)$	Response of the chamber positioned at the beam axis to photons with energy E
R_{50}	Depth in water in a beam of electrons at which the absorbed dose falls to 50% of the dose maximum
S_c	Head-scatter factor
SSD	Source-to-surface distance
TMR	Tissue-maximum ratio
VRT	Variance reduction technique
w_i	Statistical weight of the $i'th$ particle
Z	Atomic number

Chapter 1

Introduction

1.1 General introduction and thesis overview

Radiation therapy is one of the three principal modalities, the others being surgery and chemotherapy, used in the treatment of cancer. During the first 50 years of radiotherapy, following the discovery of x-rays by Roentgen in 1895, the technological progress was relatively slow and mainly based on the use of x-ray tubes. The invention of the cobalt-60 teletherapy unit by H. E. Johns in Canada in the early 1950s provided a tremendous boost in the field and placed the cobalt unit at the cutting edge of radiotherapy for a number of years.^{1,2} However, developed at the same time, medical linear accelerators (linacs) soon replaced the cobalt unit, moving through increasingly improved generations and making the contemporary machines extremely sophisticated in comparison with the machines of the 1960s. With their compact and efficient design, providing either electron or megavoltage x-ray therapy with a wide range of energies, linacs are now the most widely used radiation source in modern radiotherapy.

The process of planning a course of external-beam radiotherapy involves choosing and arranging radiation beams around the patient in order to provide the highest possible dose to the tumour while minimizing the dose to the surrounding tissues. Prior to the 1970s, treatment planning was generally carried out through the manual manipulation of standard isodose charts onto patient body contours that were generated by direct tracing. The advent of computerized tomography (CT) led to the development of CT-based computerized treatment planning, providing the ability to view dose distributions directly superimposed upon the patient's anatomy. However, both approaches require an accurate calculation of the dose distribution in the patient. Algorithms for these calculations have progressed chronologically to include analytical, matrix, semi-empirical and three-dimensional integration methods.

- The analytical technique calculated the dose in the medium as the product of two equations, one of which modeled the percent depth dose, the other modeled the off-axis component.
- Treatment planning computer systems developed in the 1970s began using the diverging matrix method of beam generation based on measured data.
- Semi-empirical dose calculation methods model the dose to a point by considering the contribution from the primary and scattered radiation independently. Based originally on the Clarkson scatter integration technique, these models have been refined by combining the formalism of basic physics with data derived from measurements.
- Three-dimensional integration methods represent transport of electrons and photons away from the primary site of interaction so as to have an accurate description of the deposition of absorbed energy while considering the geome-

try and composition of the entire volume being irradiated. These algorithms include Monte Carlo techniques for computing dose spread arrays or kernels used in convolution-superposition algorithms.^{3,4}

All mentioned dose calculation methods require an extensive set of measured data, which include dose measurements in a water phantom and also measurements in the air below the treatment head. For instance, the determination of the head-scatter factor (S_c), or collimator factor, is a key measurement in tissue-maximum ratio (TMR) dosimetry and the accuracy of the TMR based dosimetric calculations can be significantly influenced by the determination of S_c . With the advent of asymmetric and multileaf collimation it has become necessary to calculate the delivered dose at the points off central axis, and such calculations can be done by using off-axis ratios (OAR), also known as in-air profiles, along with the standard dosimetry functions.^{5,6} Furthermore, OARs are very useful in the beam commissioning process because they are very sensitive to the energy and spot size of the electrons incident on the bremsstrahlung target, as was demonstrated in the Monte Carlo (MC) studies of the output of medical linear accelerators.⁷

Another important quantity is air kerma (K_{air}), which stands for Kinetic Energy Released in the Medium, that most directly connects the description of the radiation beam with its effect.¹ Kerma is a useful concept for clarifying the principles of radiation dosimetry and it is used extensively in dosimetry calculations. For instance, in diagnostic radiology, irradiation of the patient is often monitored with the chamber measuring the air-kerma integrated over the beam area (kerma-area product meter), which can be converted to the energy imparted to the patient.⁸

Kerma is defined for indirectly ionizing radiation only (*i.e.* photons and neutrons) as the expectation value of the energy transferred to charged particles per unit

mass at a point of interest.⁹ The kerma for x - and γ -rays consists of the energy transferred to electrons and positrons per unit mass of medium. Since the kerma includes kinetic energy received by the charged particles, which may be spent by the electrons in collision or radiative type interactions, kerma can be considered to consist from two parts according to whether the energy is spent nearby in creating excitation and ionization, or is carried away by photons:

$$K = K_c + K_r , \quad (1.1)$$

where the subscripts refer to “collision” and “radiative” interactions respectively. The collision kerma concept is very important when the condition of charged particle equilibrium (CPE) holds. CPE is assumed to exist for a certain volume of material when each charged particle of a given type and energy leaving this volume is replaced by an identical particle entering, in terms of expectation values. Under condition of charged particle equilibrium at a point in a medium, the absorbed dose is equal to the collision kerma:

$$D \stackrel{\text{CPE}}{=} K_c . \quad (1.2)$$

This statement is very important because it relates a measurable quantity, the absorbed dose, to a quantity we can calculate, the collision kerma.

In clinics an uncertainty of 4-5% is now required in the delivery of absorbed dose to the target volume. However, recently radiotherapy is changing more and more into precision therapy, especially after intensity modulated radiotherapy (IMRT) has been introduced. Therefore, the accuracy of the relevant measurements is becoming crucial for successful patient treatment.

The most practical and most widely used type of dosimeter for accurate measurement of machine output in radiotherapy and diagnostic radiology is an ionization

chamber. Ion chambers have various shapes and sizes depending on specific requirements. The most popular cylindrical chamber used in radiotherapy dosimetry is the 0.6 cm³ chamber designed by Farmer.¹⁰ Its sensitive volume resembles a thimble and hence the Farmer type chamber is also known as a thimble chamber. For in-air measurements in order to provide charged particle equilibrium (CPE), the chamber is usually inserted in a build-up cap made of high- Z material with a wall thickness equivalent to the depth of the dose maximum (d_{max}), or in a low density narrow cylindrical phantom, known as a mini-phantom. Build-up caps made of brass, lead, aluminum, copper or tungsten have smaller dimensions and thus potentially provide a better resolution of the measured profiles. However, there are some drawbacks^{11–14} with this technique:

- contaminating electrons from the treatment head and the air may contribute to the measured dose;
- the depth of the dose maximum may vary with field size and beam modifying devices;
- high- Z materials and water have different interaction properties.

The greater thicknesses of the mini-phantoms are intended to convey such benefits as elimination of contamination electrons and independence from variation of d_{max} with field size.^{15–19} Another significant advantage of a mini-phantom over a build-up cap is its near tissue equivalence which is important for clinical measurements. However, due to the volume of the mini-phantom, the contribution of scattered radiation to the dose deposited in the chamber cavity may not be negligible and may therefore also lead to inaccurate measurement results.

There is a controversy in the literature concerning the advantages and disadvantages of these two methods. Some studies^{20,21} of the influence of build-up cap material on the head-scatter factor measurements have reported significant difference for build-up caps and mini-phantoms. Other investigators^{22,23} found good agreement in the results when high- Z materials are tested against phantoms of near tissue equivalence. In the investigation of low- and high- Z build-up cap materials, Weber *et al*²⁴ observed a variation in measurements up to 1% at high photon energies (10, 18 MV) and no significant differences at lower energies (4, 6 MV) measuring head-scatter factors with polystyrene mini-phantoms and build-up caps made of graphite, brass and lead. Based on a similar methods, Jursinic and Thomadsen²⁵ found larger differences (up to 4%) between their lead-cap and acrylic-cap measurements for an 18 MV beam with large field sizes. A difference up to 4.8% for a 24 MV beam and 1.5% for a 10 MV beam was reported by Frye *et al*²⁰ in experiments with mini-phantoms constructed of RMI Solid Water (Trademark of Gammex RMI) and build-up caps made of high purity graphite; head-scatter factors determined by the two methods matched well for 4 and 6 MV photon beams. Li *et al*²⁶ have compared S_c measurements and calculations performed with cylindrical mini-phantoms made of polystyrene or brass. Their data showed that the results agree within 0.5% for both 6 MV and 18 MV beams.

The problem of different build-up cap materials has been noticed not only for head-scatter factor measurements. Heukelom *et al*²⁷ reported a 3.6-% difference in wedge factors, defined as the ratio of the dose on the central axis with the wedge in place to the dose with the wedge removed (open beam), for a 4 MV beam determined using a polymethylmethacrylate (PMMA) mini-phantom and a brass build-up cap. Johnsson and Ceberg¹⁴ have reported several potential advantages of using a mini-

phantom rather than a build-up cap for OAR measurements, such as reduction of electron contamination and consistency with the proposed method of choice for head-scatter measurements. However they found no significant discrepancy between the OAR measurements performed with mini-phantom and build-up cap.

The purpose of this investigation is to study the influence of ion chamber response, including build-up cap, on in-air profiles and head-scatter factor measurements in megavoltage photon beams using MC simulations with the EGSnrc system.²⁸ BEAMnrc,²⁹ which is an upgraded version of BEAM³⁰ based on EGSnrc, is used to simulate the output of the Elekta Precise linear accelerator and the user code CAVRZnrc³¹ is employed to calculate the dose deposited in the air cavity of an ionization chamber inserted in a build-up cap made of different materials or into a plastic mini-phantom.

Basic features of the EGSnrc system, details of the accelerator simulation with BEAMnrc and dose calculation with CAVRZnrc are discussed in sections 1.2 and 1.3. Chapter 2 describes the experimental setup for the in-air profiles and scatter factor measurements performed by Malcolm McEwen with the photon beams from the Elekta Precise linear accelerator at Institute for National Measurement Standards (INMS), National Research Council Canada (NRC). One of the main goals of these experiments was to obtain high-accuracy data to compare with results of the Monte Carlo simulations, discussed in details in Chapter 3. Section 3.1 presents two new techniques developed for OAR calculations for a horizontal and a vertical orientation of the chamber. It is explained why the feasibility of those simulations is strongly dependent on the new approach. Air-kerma and head-scatter factor calculations are discussed in sections 3.2 and 3.3. Results of the MC simulations, a comparison with the measurements and an analysis of the effect of the different build-up caps are given

in Chapter 4. Chapter 5 presents conclusions of this investigation.

1.2 EGSnrc code system

1.2.A Overview of EGSnrc

EGSnrc is a general purpose package of computer codes for the Monte Carlo simulation³² of the coupled transport of electrons and photons. EGSnrc is an enhanced version of the EGS4^{33,34} system (Electron-Gamma-Shower, version 4), that includes a variety of improvements in the underlying cross sections and in the condensed history simulation of charged particle transport. It can simulate photon and electron interactions with matter in an arbitrary geometry and in any element, compound or mixture. The dynamic range of the simulated charged particle kinetic energies goes from a few tens of keV up to a few hundred GeV. The dynamic range of photon energies lies between 1 keV and several hundred GeV.

In order to provide an accurate simulation with the MC technique, it is necessary to take into account all the relevant physical processes. As a photon passes through matter it interacts via four basic processes: incoherent (Compton) scattering with atomic electrons, production of an electron-positron pair in the electromagnetic field of the nuclei and surrounding atomic electrons, photoelectric absorption and coherent (Rayleigh) scattering with the molecules or atoms of the medium.

For photon energies of the order of 1 MeV, the dominant interaction is Compton scattering in which the photon scatters from an atomic electron and sets it in motion. In many calculations it is adequate to consider this electron as free, but at lower energies the cross sections are affected by the fact that the electron is ini-

tially bound in an atom. The treatment of the Compton process in EGSnrc is based on the relativistic impulse approximation that includes binding effects and Doppler broadening. Optionally the user may select the Compton process modeling according to the Klein-Nishina formula, which describes photon scattering with a free electron initially at rest.

At photon energies above a few MeV, pair production begins to dominate. In this case the photon interacts with the field of the nucleus, is absorbed and creates an electron-positron pair. Much less frequently the photon may interact with the field of an atomic electron, which can take up a considerable amount of energy and leave the atom with a vacancy. The process is referred to as triplet production. In the EGSnrc system the triplet production is not simulated explicitly but taken into account in an approximate way by using the total pair plus triplet cross section to sample distances to subsequent pair production collisions. EGSnrc adopts the cross sections used in EGS4, *i.e.* extreme relativistic Born approximation differential cross section (Coulomb corrected above 50 MeV), formulated in the article by Motz, Olsen and Koch.³⁵

At lower photon energies the predominant photon interaction is the photoelectric effect, in which the photon is absorbed by the atom and a photoelectron is emitted with an energy given by the incident photon energy minus its binding energy. The atom, left in an excited state with a vacancy in the ionized shell, relaxes via the emission of fluorescent photons (K, L, M shells are considered in EGSnrc) as well as Auger and Coster-Kronig electrons.³⁶

The last major photon interaction, occurring at low energies, is Rayleigh (or coherent) scattering, in which the photon scatters elastically from atoms or molecules in the material. No energy is lost by the photon except for a negligible amount to the

atomic recoil. EGSnrc treats Rayleigh scattering using the total coherent scattering cross sections from Storm and Israel³⁷ and the atomic form factors from Hubbell and Øverbø.³⁸

Electrons lose energy in matter by two basic processes: inelastic collision with atomic electrons and radiation. Radiative energy loss occurs in the form of bremsstrahlung and positron annihilation. The bremsstrahlung process is the dominant mechanism of electron energy loss at high energies and inelastic collisions are more important at low energies. Inelastic electron collisions and photon interactions with atomic electrons lead to excitations and ionizations of the atoms along the path of the particles. Highly excited atoms with vacancies in inner shells relax via the emission of photons and electrons with characteristic energies.

In Monte Carlo simulations it is time consuming and often not possible to simulate each interaction individually because an electron undergoes a large number of elastic scatterings from nuclei. Also, in the course of slowing down a large number of low energy “knock-on” electrons are set in motion and many atoms are left in excited states. To avoid this difficulty, Berger³⁹ developed the “condensed history” (CH) technique for the simulation of charged particle transport. In this method, large numbers of subsequent transport and collision processes are “condensed” to a single electron step. Thus, the path of the electron is broken into a series of steps, for which the effects of the large number of individual interactions occurring during the step are grouped together. The cumulative effect of the individual interactions is taken into account by sampling the change of the particle’s energy, direction of motion and position at the end of the step from appropriate multiple scattering distributions. The CH technique, motivated by the fact that single collisions with the atom cause only minor changes in the particle’s energy and direction of flight, made the MC

simulation of charged particle transport possible.

Berger defined two basic classes of CH implementation, which are distinguished by how they treat individual events that lead to bremsstrahlung photons and delta electrons. In a class *I* scheme, the effects on the primary electron of all interactions of a certain type are grouped together for each condensed history step. This means that particles move on a predetermined energy loss grid: the energy losses and angular deflections associated with all individual events are grouped together and the energy and direction of the primary electron are not affected by the creation of individual secondary particles. Although such a scheme has a potential for a more accurate treatment of multiple elastic scattering, there are some disadvantages associated with the lack of correlation between energy loss and secondary particle production, as well as the necessity for difficult interpolations when the particle steps do not conform to the predetermined grid. In a class *II* scheme, inelastic collisions resulting in the emission of bremsstrahlung and delta particles with energy above given thresholds are treated explicitly, as they affect the energy and direction of the primary electron. Such interactions are referred to as “catastrophic” or discrete interactions. Subthreshold processes are accounted for in a continuous-slowng-down approximation (CSDA) model and are subject to grouping. The choice of the energy thresholds for considering the creation of secondary particles as discrete events is arbitrary and a component of the algorithm, not of the physical processes involved.

EGSnrc uses a class *II* CH scheme for the simulation of electron transport. Bremsstrahlung processes that result in the creation of photons above a photon energy threshold (AP) and inelastic collisions that set in motion atomic electrons with kinetic energies above an electron energy threshold (AE), are both simulated explicitly and the secondary particles are transported. Table 1.1 summarizes some definitions of energy

Table 1.1: Definition of energy thresholds and cutoffs used in EGSnrc.

Definition	Electrons Positrons	or Photons	Meaning
Energy cutoffs	ECUT	PCUT	Particle histories are terminated for particles with kinetic energies below these values
Production thresholds	AE	AP	The production by electrons of secondary particles with kinetic energy greater than these values is modeled explicitly

cutoffs and thresholds. Energy cutoffs (PCUT and ECUT) are used in both class *I* and class *II* algorithms, while the production thresholds apply only to class *II* algorithms. EGSnrc models bremsstrahlung production using either Bethe-Heitler⁴⁰ cross sections or the NIST⁴¹ cross sections. In the treatment of inelastic scattering, EGSnrc ignores the binding of atomic electrons and implements the Møller cross section for electron-electron scattering and the Bhabha cross section for positron-electron scattering.

1.2.B Statistical uncertainties

The Monte Carlo method simulates particle transport processes in a physically realistic way: particles are “born” according to distributions describing the source, they travel certain distances, specified by a probability distribution depending on the total interactions cross section, to the site of a collision and scatter into another energy and direction according to the corresponding differential cross section, possibly producing new particles that have to be transported as well. This procedure is continued until all particles are absorbed or leave the geometry under consideration.

Quantities of interest can be calculated by averaging over a given set of MC particle “histories”. From a mathematical point of view each particle “history” is one point in a d -dimensional space (the dimensionality depends on the number of interactions) and the averaging procedure corresponds to a d -dimensional Monte Carlo integration. The MC estimate of quantities of interest is subject to a statistical uncertainty, depending on the number of simulated histories N and decreases as $N^{-1/2}$. EGSnrc handles the statistical uncertainty using the history by history method.⁴² In this method the uncertainty in the average of a scored quantity X is defined as:

$$S_{\bar{X}} = \sqrt{\frac{1}{N-1} \left(\frac{\sum_{i=1}^N X_i^2}{N} - \left(\frac{\sum_{i=1}^N X_i}{N} \right)^2 \right)}, \quad (1.3)$$

where X_i is the quantity scored in statistically independent event i (i.e., history), N is the number of independent events (histories). The uncertainty can be calculated at the end of the simulation by keeping track of $\sum_{i=1}^N X_i^2$ and $\sum_{i=1}^N X_i$ on the fly. The problem is that when there is a large number of quantities being scored, it can be very computationally inefficient to evaluate $\sum_{i=1}^N X_i^2$ at the end of each history. To overcome this problem, Sempau *et al*⁴³ outlined a clever algorithm, which is implemented in all EGSnrc user codes.

Some output quantities are ratios of correlated quantities. In order to estimate the uncertainty on the ratios using a history by history method, the equation for the fractional uncertainty on a ratio of correlated quantities ($C = X/Y$) has been used:

$$\frac{S_{\bar{C}}}{\bar{C}} = \sqrt{\left(\frac{S_{\bar{X}}}{\bar{X}} \right)^2 + \left(\frac{S_{\bar{Y}}}{\bar{Y}} \right)^2 - \frac{2cov(X, Y)}{(N-1)(\bar{X} \bar{Y})}}, \quad (1.4)$$

where $S_{\bar{X}}$ and $S_{\bar{Y}}$ are the uncertainties on $\bar{X}$ and $\bar{Y}$ estimated using the history by history method outlined above, and $cov(X, Y)$ is the covariance of X and Y , given by:

$$cov(X, Y) = \frac{\sum_{i=1}^N X_i Y_i}{N} - \frac{\sum_{i=1}^N X_i}{N} \frac{\sum_{i=1}^N Y_i}{N}. \quad (1.5)$$

In order to calculate $cov(X, Y)$, one must keep track of $\sum_{i=1}^N X_i Y_i$ on a history by history basis. This is done on the fly using an algorithm similar to the one used to keep track of $\sum_{i=1}^N X_i^2$ and $\sum_{i=1}^N X_i$.

A history by history statistical estimation has been implemented in all EGSnrc user codes and in the BEAMnrc code.

1.2.C Variance reduction techniques

The efficiency ε of a MC calculation is defined as

$$\varepsilon = \frac{1}{T\sigma^2}, \quad (1.6)$$

where σ is the statistical uncertainty of the quantity of interest and T is the CPU time needed to obtain this uncertainty. Techniques that improve ε without altering the physics are known as variance reduction techniques (VRTs).^{44,45} Realistic Monte Carlo calculations can take many hours of computing time, hence the use of appropriate VRTs is very important. Options for three variance reduction techniques are implemented directly into the EGSnrc system: range rejection, bremsstrahlung splitting and Russian Roulette.

Range rejection can save significant quantities of computing time for electron transport calculations. The basic method is to calculate the range of a charged particle and terminate its history (depositing all of its energy at this point) if it cannot leave the current region since its residual range is shorter than the distance to any region boundary. In BEAMnrc a threshold energy (or the range rejection cutoff energy ECUTRR) is automatically calculated for each region such that an electron must be able to escape the region with the energy greater than ECUTRR. If its energy is less than ECUTRR, the particle cannot reach the scoring region of interest. 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 photons that would have been created by the particle do not leave the current region as well. The effects of this approximation can be minimized by setting a maximum energy for which a history can be terminated (**ESAVE**) thus allowing the higher energy electrons to create bremsstrahlung photons which can escape from the region. Therefore, the approximation can be made very accurate while still obtaining significant gains in efficiency.

Bremsstrahlung splitting is a technique which can provide a factor of 4 or more improvement in efficiency when modeling photon beams generated by medical accelerators.³⁰ It is implemented as follows. Each time an electron emits a photon the simulation emits an arbitrary number of bremsstrahlung photons with their weight suitably reduced. The electron's energy is decreased by the energy given off by one of these photons. Once set, EGSnrc will split bremsstrahlung at all generations.

Russian Roulette is a standard variance reduction technique. In contrast to splitting, which serves to create many particles out of one, Russian Roulette combines several particles to one, increasing the weight of the survivor. It works as follows. If a random number r is less than a survival probability p , then the particle is "killed", otherwise it is kept and its weight increased by $1/p$.

Some other variance reduction techniques, implemented in CAVRZnrc and BEAMnrc are discussed in the following sections.

1.2.D CAVRZnrc

To use the EGSnrc code system, which only provides various physics routines, a “User Code” is required. It consists of a MAIN program and the subroutines determining the geometry and the scoring of the quantities of interest. The descriptions of the user codes developed at NRC for cylindrical RZ geometries are summarized in Table 1.2. Collision a

Table 1.2: EGSnrc user codes for for cylindrical RZ geometries.

User code	Description
DOSRZnrc	scores dose in a generalized cylindrical geometry
FLURZnrc	scores particle fluence in the same geometry
CAVRZnrc	is similar to DOSRZnrc but also scores a variety of quantities which are of specific interest to dosimetry calculation for an ion chamber
SPRRZnrc	calculates Spencer-Attix spectrum averaged stopping-power ratios for arbitrary media

In our study the user code CAVRZnrc³¹ was employed to calculate the response of an ionization chamber surrounded by a build-up cap or a mini-phantom. CAVRZnrc is optimized for the calculation of the dose deposited in the cavity of an ionization chamber and therefore is best suitable for our investigation. The actual geometry and its approximation in the CAVRZnrc simulation are shown in Fig. 1.1. The conical shape of the chamber and the build-up cap tip is simulated as a cylinder with the same thickness as the cone height or with a thickness that results in the same volume (this issue is discussed in more detail in Chapter 3). Geometrical inputs

for CAVRZnrc simulations have to include information on all planar and cylindrical ring zones and each geometrical region is associated with a certain material from the PEGS4 cross section data file. An additional set of inputs defines the region of the ion chamber cavity.

Some of the particle sources implemented in CAVRZnrc and used in our simulations are listed in Table 1.3. For a horizontally oriented chamber, the photon beam emerging from the accelerator was approximated by a point source, modeled using source 15. For a vertically oriented chamber the new source type 23, utilizing a BEAMnrc shared library has been developed specifically for OAR calculations. Its advantages over the full phase-space data are discussed in section 3.1.B.

Table 1.3: Description of the particle sources implemented in CAVRZnrc used in the simulations.

Source number	Description
1	Point source on axis incident from the front
11	Point source incident from the side
15	Point source incident from any angle
22	Full beam phase-space data incident from any angle
23	BEAMnrc user code shared library

In addition to the variance reduction techniques implemented in the EGSnrc code directly, the following methods are incorporated in CAVRZnrc: pathlength biasing, photon interaction forcing, photon cross section enhancement and photon splitting. The first two are employed in all RZ user codes; the last two are specific for

Figure 1.1: Ion chamber with the build-up cap. I - build-up cap geometry; II - CAVRZnrc approximation as a cylinder with the same thickness as the cone height. 1 - build-up cap material, 2 - graphite wall, 3 - PTCFE insulator, 4 - aluminum electrode, 5 - air cavity.

CAVRZnrc.

The photon splitting technique⁴⁵ applied in CAVRZnrc may increase the efficiency of cavity dose calculations by a factor of 3 compared to using only the photon forcing. It works as follows: each photon that is to be transported is split into n_{split} photons with weights W_0/n_{split} , where W_0 is the original photon weight. The number of mean-free-paths λ_i to the next interaction of the i 'th such photon is sampled from

$$\lambda_i = -\ln \left(1 - \frac{r + i - 1}{n_{\text{split}}} \right), \quad (1.7)$$

where i runs from 1 to n_{split} and r is a random number. This forces a uniform distribution of interaction sites. Because of the condition $\lambda_{i+1} > \lambda_i$ only the transport from λ_i to λ_{i+1} is needed to get to the interaction site of the $i + 1$ 'st photon from the interaction site of the i 'th photon. When one of the split-photons interacts, all resulting scattered photons are killed with the probability $1/n_{\text{split}}$ and marked as scattered if they survive.

In our CAVRZnrc simulations the following variance reduction techniques were used: electron range rejection and photon splitting with a splitting number of 250.

1.3 BEAMnrc

1.3.A Overview of BEAMnrc

BEAMnrc,²⁹ which is an improved version of BEAM,³⁰ is a general purpose Monte Carlo code to simulate the radiation beams from radiotherapy units, based on the EGSnrc system for simulating radiation transport. An important feature of this code is the ability to produce a phase-space output of the beam (i.e., the positions, energies,

directions, *etc*, for each particle) at any specific plane in the model. This phase-space file can either be reused by the BEAMnrc code itself, or used as a particle source for other EGSnrc user codes.

The model of the radiation source is built up from the series of individual component modules (CM), which are completely independent and can be used in a wide variety of applications. Each CM deals with a specific class of geometric shapes within the horizontal band of the accelerator. Thus, the therapy source model consists of a series of component modules, each contained between two planes which are perpendicular to the Z axis (taken as the beam axis) and cannot overlap. The CMs have been named after the components they were originally written to model, but they can be applied to many more structures. The component modules used to build the Elekta Precise linac with the BEAMnrc simulation are shown in Table 1.4.

BEAMnrc has three major forms of output. The listing file is always present and optionally BEAMnrc can produce a phase-space file and/or a graphics file, which shows the accelerator geometry and every step in the particle's history. The listing file is the primary record, specifying all the input information of an accelerator model and containing several standard outputs, including a variety of fluence related parameters scored at the arbitrary number of scoring planes. The phase-space files contain the data about each individual particle crossing the scoring planes. Fig. 1.2 represents a graphics output of the simulation giving a simplified 3-D image of the treatment head geometry of a linac.

For estimation of statistical uncertainties the history by history method, described earlier, is implemented in BEAMnrc. This method involves grouping scored quantities according to primary history during a run. For most sources, there is no difference between a primary history and an incident particle. However, for phase-

Table 1.4: Component Modules (CM) of the BEAMnrc simulation used to build an Elekta Precise linear accelerator.

CM	Description
SLABS	Used for multiple planes of arbitrary thickness and material which are perpendicular to the Z axis. The outer boundary is square. SLABS is often used to model the bremsstrahlung target in photon accelerators.
CHAMBER	Models an ionization chamber and many other structures with cylindrical symmetry and centered on the beam axis. For a monitor chamber, both the front and back walls may have several layers of different material. CHAMBER can also be used to score the central axis dose in a water phantom outside the accelerator.
CONESTAK	Used to simulate a stack of truncated cones. A primary collimator is a special case for CONESTAK using only one cone. The inner and outer conical regions of each layer have their materials specified separately. CONESTAK is rotationally symmetric about the beam axis.
FLATFILT	Is the most complex CM, which is basically the generalization of a CONESTAK to an arbitrary number of truncated conical sections on each layer. In particular, FLATFILT can handle a flattening filter inside a conical collimator.
MIRROR	Used to simulate mirrors in the accelerator. It can have any angle with respect to Z axis. The number of layers and the thickness, materials in the mirror can be arbitrary. The outer boundary is square centered on the beam axis.
JAWS	Models pairs of opposing flat surfaces which are perpendicular to the X or Y axis. The JAWS surfaces may be at an arbitrary angle with respect to the Z axis. The outer boundary is a square centered on the beam axis.

Figure 1.2: BEAMnrc simulation of an Elekta Precise linear accelerator. Yellow lines show the photon tracks.

space sources, where more than one particle can be traced back to a single primary history, it is important to group according to primary history in order to account for correlations between the incident particles (for more details of the method see 1.2.D of Chapter 1).

For enhanced efficiency of computer calculations the following variance reduction techniques are employed in BEAMnrc: range rejection and directional bremsstrahlung splitting (DBS).

Directional bremsstrahlung splitting⁴⁶ was introduced into BEAMnrc in 2004 and results in much better efficiency for photon beam simulation. The main idea is that bremsstrahlung photons aimed into a field of interest (encompassing the treatment field) are split at the time of creation, while those aimed away from the field are not. The outline of the DBS algorithm is as follows. If a charged particle undergoes a bremsstrahlung or annihilation event, then DBS splits this event **NBRSPL** times, where **NBRSPL** is the splitting number. The resulting photons all have their weight multiplied by NBRSPL^{-1} . DBS then loops through these split photons and for each one determines whether or not it is aimed into the splitting field, defined by the radius of the splitting field (**FS**) and source to surface distance (**SSD**). If it is, the photon is kept and considered “non-fat” (low-weight). If not, then Russian Roulette is played on the photon by comparing a random number to a survival threshold of NBRSPL^{-1} . If the random number is less than this number, then the photon is kept and its weight is multiplied by NBRSPL^{-1} and is considered as a “fat” (high-weight) photon. Splitting is not limited to bremsstrahlung and annihilation events. If one of those fat photons undergoes a Compton event, then it is also split **NBRSPL** times and the same Russian Roulette scheme as above is applied to photons not aimed into the splitting field. DBS results in many non-fat photons inside the splitting field and few fat photons

outside the splitting field. All of the non-fat photons inside the splitting field will have the same low weight (NBRSP^{-1} times the weight of the incident particles).

BEAMnrc can handle a wide variety of input source geometries and input beams of different particles, including electrons, photons or positrons. To simulate the output of an Elekta Precise linac we used a parallel circular electron beam with a 2-D Gaussian X-Y distribution, in which the incident electrons have identical Gaussian distributions in the X and Y directions resulting in a 2-D Gaussian distribution of particles, modeled by source 19.

1.3.B Elekta Precise linac simulation details

For the BEAMnrc simulation of an Elekta Precise linac output we used initial geometry dimensions from Sheikh-Bagheri and Rogers⁷ but modified significantly based on up-to-date data from Elekta.

The transport parameters used in the linac simulation were as follows. The values of the electron (ECUT) and photon (PCUT) cutoff energies were 0.700 MeV and 0.010 MeV respectively. Electron range rejection was set on with a global electron “save” rejection energy (the parameter ESAVE) of 2 MeV. The low energy thresholds for the production of secondary bremsstrahlung photons (AP) and knock-on electrons (AE) were selected to be equal to PCUT and ECUT respectively. To improve the efficiency of the treatment head simulations the directional bremsstrahlung splitting (DBS) technique⁴⁶ was employed with a splitting radius (FS) of 30 cm, a source to surface distance of (SSD) 100 cm and splitting number (NBRSP) varying between 400 and 1000. The number of histories used in the simulations varied between 10^6 and 10^7 .

Chapter 2

Experimental method

2.1 Chamber type and different build-up caps

In-air profiles and head-scatter factors measurements were performed by Malcolm McEwen at IRS/INMS, NRC. In the experiments he used 6, 10 and 25 MV photon beams from an Elekta Precise linear accelerator.⁴⁷ Build-up caps of hevimet (a tungsten alloy consisting of 90% W, 5% Ni and 5% Cu) and brass were used together with two cylindrical PMMA mini-phantoms of different sizes. The details are shown in Table 2.1. It was not possible to exactly match the wall thicknesses of each cap due to manufacturing issues but the wall thickness for each cap is greater than the depth of maximum dose for all beams investigated here, except for the small PMMA mini-phantom at 25 MV.

Five chamber types were used in the investigation - NE2571, NE2505/3, NE2581, PTW30001 and PTW233642. The NE2571 and NE2505/3 are both graphite-walled Farmer chambers, differing only in the internal construction of the chamber

Table 2.1: Physical data for the build-up caps used in this investigation.

Material	Diameter,mm	Height,mm	Wall thickness,g/cm ²	Density,g/cm ³
Hevimet	14.20	35.00	6.10	16.94
Brass	22.00	39.75	5.76	8.47
PMMA small	59.04	79.82	3.10	1.19
PMMA large	92.74	116.08	5.10	1.19

stem. The NE2581 is basically the same except having an electrode and wall constructed of A-150 plastic and a larger diameter central electrode – 3 mm rather than 1 mm for the NE2571. The PTW30001 (now model PTW30010) is an acrylic walled Farmer chamber while the PTW233642 (now model PTW31010) is a 0.125 cm³ acrylic-walled scanning chamber.

It was found that there was generally very good agreement between all the chambers used. Although differences of up to 1% were seen, some of those are likely to be due to real variations in the beam output. Typically, differences were less than 0.5% with no systematic change in the shape of the profile. Although it might be expected that all the Farmer type chambers would agree, it was gratifying to confirm that the small constructional differences between these chamber types have no significant effect. The agreement between the 0.6 cm³ chambers and the 0.1 cm³ is important as neither the mini-phantom nor the build-up cap covered the stem of either chamber type. The agreement seen indicates that stem effects do not significantly affect these measured beam profiles and reduces the level of detail required in the Monte Carlo model. Parameters of the Farmer chamber NE2571 were used in the MC simulation.

2.2 In-air profile measurements

To measure in-air profiles, an ion chamber was mounted on a Multidata Systems International Corp. 3-D scanning system, as shown in Fig. 2.1. A vertical beam was used throughout. The first picture (left) shows the linac and scanning system with a chamber setup for a gun-target (G-T) scan. The phantom was empty and the chamber was raised to its highest position so that scatter from the phantom walls, scanning frame, *etc* was minimized. The centre picture of Fig. 2.1 shows a chamber aligned vertically (end-on to the beam) with the smaller of the two PMMA mini-phantoms while the picture of the right shows a chamber aligned horizontally (side on to the beam) with a hevimet build-up cap. For the scans with the chamber side-on to the beam the scan direction was perpendicular to the axis of the chamber. The distance was set to be 1 m (± 1 mm) to the thimble of the chamber without build-up cap in place and the field size was set to 40x40 cm² at this distance. The software supplied with the Multidata phantom was used to acquire the data - the total scan was 44 cm (22 cm each side of the central axis), the step size was 1 or 2 mm and the integration time at each point was 0.4 s. This combination of parameters resulted in a total scan time around 4 minutes. A brief investigation showed that the choice of linac dose rate (pulse repetition frequency) did not affect the acquired beam profile.

One of the primary aims of the experiments was to obtain high-accuracy data and therefore a series of investigations of influence quantities was carried out. Multiple scans were acquired on different days to look at the issue of repeatability. It was found that there was very good agreement between scans obtained on the same day - typically better than 0.3% - although there was some evidence of a slight warm-up effect at the beginning of the day. There were larger variations between scans

Figure 2.1: Experimental setup for in-air profiles measurements. The first picture (left) shows the linac and a scanning system; a chamber with a PMMA mini-phantom aligned vertically is shown in the center; a chamber aligned horizontally with a hevimet build-up cap is on the right.

acquired on different days but these were generally less than 1% and no more than 2% maximum. Data was acquired over a period of 8 months and no long term drift in the beam profile shape was seen, *i.e.* month-to-month variations were similar to those from day-to-day. Fig. 2.2 shows typical data. It was found that, as expected, there was no effect due to the polarity of the voltage applied to the scanning chamber. No recombination correction was applied to the data since the focus of this study was the main field region where the variation of dose is less than 10%.

1-D scans were acquired in the G-T (otherwise known as “in-plane”) and A-B (also known as “cross-plane”) directions with the chamber thimble centered on the fixed axis. The scanning phantom was rotated 90 degrees between the two directions so that the same scanning axis was used for all scans. This also meant that scanning along the chamber axis was avoided, so there is no differential stem effect between the two scanning planes. It was found that for all three energies there was a difference in the shapes of the profiles for the two directions. No difference was seen for the scans in the same direction but with the head (collimating jaws) rotated by 90 degrees, indicating that this effect is due to the beam steering and primary beam shaping system of the linac. Although changes in the profiles could be made by manually controlling the beam steering it was not possible to exactly match the two scan directions. It was also found that the FWHM of the plot was approximately 5 mm less for the A-B scan than the G-T scan.

As can be seen from Fig. 2.2, all profiles show some asymmetry. In general for this linac the G-T scans showed less asymmetry than the A-B scans and therefore only G-T scans were used for a comparison with MC calculations. Since the MC simulations assume a symmetrical beam profile, the average of the two sides was taken as the best estimate of the measured profiles.

Figure 2.2: Comparison of G-T scans for a 10 MV beam obtained on different days. Variations between scans are generally less than 1%.

The overall uncertainty of the measurements is approximately 0.6%. It was estimated from the random point-to-point noise on a single scan (typically 0.1-0.2%), variations within a day and day-to-day differences (0.2-0.5%) and the asymmetry of the measured profiles (about 0.2%).

It was found that there were significant differences in the scans with the chamber side-on or end-on to the beam. This is discussed in detail in the next Chapter.

2.3 Head-scatter factor measurements

The Head-scatter factor S_c is determined as the ratio of the dose measured for an arbitrary field to the dose measured at the reference collimator setting, usually for a nominal field of 10x10 cm² and the nominal SSD, as follows:

$$S_c = D(r)/D(10) , \quad (2.1)$$

where $D(r)$ is the dose to the air cavity of an ion chamber inserted in a build-up cap measured on the beam axis for a field of size r and $D(10)$ is the dose, measured for the reference field of 10x10 cm². Thus, S_c is normalized to 1 for the nominal field of 10x10 cm² at the nominal SSD for the treatment machine (for Elekta linac the standard SSD is 100 cm). The head-scatter factor is larger than 1 for fields exceeding the nominal field and smaller than 1 for fields below 10x10 cm².

The head-scatter factor measurements were performed with the NE2571 chamber used in the in-air profiles measurements. The same build-up caps made of hevimet and brass along with the smaller of the two PMMA mini-phantoms were used in the experiments. The experimental setup for the head-scatter measurements using the PMMA mini-phantom is shown in Figure 2.3. A low scatter arrangement was used

Figure 2.3: Experimental setup for head-scatter factor measurements. Ionization chamber surrounded by a PMMA mini-phantom is shown. The linac pointer is removed prior to irradiation.

to minimize the material near the mini-phantom. All material is outside the beam except for the two hollow aluminum tubes supporting the mini-phantom.

Ionization data were acquired for square fields in the range $7 \times 7 \text{ cm}^2$ to $40 \times 40 \text{ cm}^2$. The ion chamber, inserted in a build-up cap or a mini-phantom, was fixed in position on the radiation beam axis side-on to the beam. The distance was set to be 1 m ($\pm 1 \text{ mm}$) to the outside of the graphite thimble of the chamber. The photon beams of 6 and 10 MV were used in the experiments. The highest energy beam was not considered for this experiment because the thickness of the smaller PMMA mini-phantom is not sufficient to provide the maximum dose build-up at 25 MV and the large mini-phantom cannot be used for the small fields measurements. Therefore, we could not compare effect of the high- and low- Z material build-up caps in this photon beam.

Fig. 2.4 shows head-scatter factors measured with different build-up caps in 6 and 10 MV photon beams. Experiments demonstrate about 1% difference between the hevimet build-up cap and the PMMA mini-phantom for large field sizes (from $20 \times 20 \text{ cm}^2$) at 10 MV and about 0.5% difference at 6 MV. Measurements made with the brass build-up cap are in between the higher Z hevimet and lower Z PMMA. These results are consistent with those reported by Weber *et al.*²⁴ In their investigation they have used lead, brass and graphite build-up caps and the results were compared with measurements taken using square and cylindrical polystyrene mini-phantoms. The intercomparison between the two different plastic mini-phantoms and graphite caps showed no difference. However, the use of lead and brass build-up caps produces normalized head-scatter factor different (1%) from graphite build-up caps (and mini-phantoms) for large fields at 10 and 18 MV. At lower energies, 4 and 6 MV, insignificant differences (less than 0.5%) were found.

Figure 2.4: Head-scatter factors measured with different build-up caps and the smaller mini-phantom in a 6 MV (upper graph) and in a 10 MV (lower graph) photon beam from an Elekta linac.

Chapter 3

Simulation techniques

3.1 Calculation of in-air OARs

To calculate in-air OARs we needed to compute the dose deposited to the cavity of the ionization chamber, surrounded by a high- Z material build-up cap or a plastic mini-phantom, placed in air, as a function of the distance from the beam axis. For this purpose it was necessary to perform separate dose calculations for different chamber positions relative to the beam central axis. The traditional approach of using the results of a treatment head MC simulation for a dose calculation is to store the particles emerging from the head in a phase-space file and then to use this phase-space file as a source for the dose calculation in the geometry of interest. In the situation investigated here, the geometry (ion chamber plus build-up cap) is typically very small compared to the area of the simulated $40 \times 40 \text{ cm}^2$ field. For instance, when the chamber is oriented vertically and a hevimet build-up cap is used, the effective area exposed to the beam is only of the order of 1.6 cm^2 which means that approximately only one out of 1000 particles in the phase-space file will enter the simulation

geometry. For this situation the EGSnrc user code CAVRZnrc transports on the order of 50000 particles per second and therefore approximately 5×10^7 particles per second need to be read from the phase-space file to supply the CAVRZnrc simulation with particles. A BEAMnrc phase-space file containing 5×10^7 particles corresponds to about 1.5 GB of data. This is more than an order of magnitude beyond the speed of currently available hard disks. The situation can be somewhat improved by using the photon splitting feature of the RZ series EGSnrc user codes.³¹ By splitting each photon from the phase-space file 200 times, the time needed to read the phase-space data can be made comparable to the time needed for the particle transport through the chamber geometry when using a single CPU. However, in a parallel run the limited speed of the network becomes the bottleneck of the calculation. Given these observations, it should be clear that alternative simulation techniques were needed to perform the in-air OAR calculations. The techniques developed in the course of this investigation are described in the next two subsections.

3.1.A Horizontally oriented chamber

When the chamber is oriented horizontally (*i.e.* its axis is perpendicular to the beam axis, as shown in Fig. 3.1), a point source located at a distance d from the chamber positioned on the central axis “sees” the chamber at a distance x from the axis in essentially the same way due to cylindrical symmetry, except that the solid angle is reduced by $d^2/(d^2 + x^2)$. This implies that the response of the chamber $R(E, x)$ at position x will be given by

$$R(E, x) = R(E) \frac{d^2 + x^2}{d^2} , \quad (3.1)$$

Figure 3.1: Cross section of the horizontally oriented ion chamber at different distances from the beam axis. Photon beam emerging from the accelerator is approximated as a point source.

where $R(E)$ is response of the chamber positioned at the beam axis to photons with energy E , defined as the dose $\tilde{D}(E)$ to the chamber cavity per incident photon fluence Φ_0 :

$$R(E) = \frac{\tilde{D}(E)}{\Phi_0} . \quad (3.2)$$

For a point source with a spectrum $f(E, x)$ (number of photons per unit energy interval per unit solid angle) varying with the distance x from the central axis, the fluence $\Phi(E, x)$ is given by

$$\Phi(E, x) = \frac{f(E, x)}{d^2 + x^2} . \quad (3.3)$$

Hence, the dose $D(x)$ to the cavity when the chamber is at position x from the point source with spectrum $f(E, x)$ is simply

$$D(x) = \frac{1}{d^2} \int dE f(E, x) R(E) . \quad (3.4)$$

Equation (3.4) implies that if the output of the linear accelerator is assumed to be well approximated by a point source with a spectrum varying with distance from the beam axis and if the response $R(E)$ to photons with energy E is pre-calculated and tabulated for fast run-time interpolation, $D(x)$ can be calculated on the fly within the beam simulation by simply using

$$D(x) = \frac{1}{N} \sum_{i \in x} \frac{w_i}{|\cos \theta_i|} R(E_i) , \quad (3.5)$$

where N is the number of electrons incident on the bremsstrahlung target and w_i, E_i are the weight and energy of the i 'th particle crossing the scoring plane around location x and θ_i is the angle between the particle direction and the plane normal. In reality the photon beam emerging from the accelerator is not a point source. However, most of the emerging photons are created in the bremsstrahlung target and these photons are well approximated by a point source due to the chamber distance being much larger compared to the typical spot size of medical linacs. In addition, even scattered

photons are typically produced at a large distance from the chamber so that the effect of fluence variation of the scattered radiation sources due to varying solid angles as the chamber moves along the profile are very small. Therefore Eq. (3.4) is expected to be highly accurate, except near the edges of the field. When the ion chamber is close to the edge, part of the build-up cap is outside of the field. The accuracy of the method is reduced because the tabulated response functions are for a fully irradiated chamber plus build-up cap. Because of the smaller dimensions of the build-up caps, this effect is expected to be more pronounced for the mini-phantoms and this was indeed confirmed by the results of the simulations (see section 4.1). The advantage of using Eq. (3.4), or Eq. (3.5), is that the calculation of a complete OAR profile is very fast (typically less than 30 minutes using 20 CPUs for a statistical uncertainty of 0.3% or better for all OAR profile points).

The response function $R(E)$ to photons with energy E was computed with the EGSnrc user code CAVRZnrc (see section 1.2.D), using a point source for each of the 4 build-up caps used in the measurements in the energy range 0-25 MeV to a statistical uncertainty of 0.2% or better. The calculation energy grid was gradually refined to guarantee that the linear interpolation in the logarithm of the photon energy used at run-time is better than 0.1%.

The conical shape of the chamber and build-up cap tips cannot be simulated with CAVRZnrc which is only able to model cylindrically shaped geometries. Fig. 1.1 shows the geometry of the build-up cap and its approximation as a cylinder used in the CAVRZnrc simulation. To investigate the effect of this geometry approximation on computed results, the response $R(E)$ was calculated with the conical tips modeled as a cylinder with the same thickness as the cone height (approach 1) or with a thickness that results in the same volume (approach 2) and it was found that simulated OAR

profiles with both response functions demonstrate a negligible difference within the statistical uncertainty.

Fig. 3.2 presents $D(E)/K_{\text{air}}(E)$ as a function of photon energy. Using Eq. (3.2) and the definition of the air-kerma for a monoenergetic photon beam in air:

$$K_{\text{air}} = \Phi_0 E \left(\frac{\mu_{\text{tr}}(E)}{\rho} \right)_{\text{air}}, \quad (3.6)$$

we can make the following transformation:

$$\frac{R(E)}{E (\mu_{\text{tr}}(E)/\rho)_{\text{air}}} = \frac{D(E)}{K_{\text{air}}(E)}. \quad (3.7)$$

Here $R(E)$ was calculated according to approach 2 and the mass energy transfer coefficients $(\mu_{\text{tr}}(E)/\rho)_{\text{air}}$ were taken from the tables of Hubbell and Seltzer.⁴⁸ Fig. 3.2 clearly demonstrates that the dose to the chamber per unit air-kerma is much less energy dependent when using PMMA mini-phantoms compared to brass or hevimet. Hence, one can expect the mini-phantom arrangement to show much less dependence on the spectrum variation with off-axis distance.

3.1.B Vertically oriented chamber

When the chamber is oriented vertically, particles can enter from the top or the side with the relative fraction of particles entering from the side increasing with increasing distance from the beam axis (see Fig. 3.3). Therefore, the arguments presented in the previous section do not apply in this case and instead, a full simulation for each chamber off-axis distance is needed.

As discussed earlier, such full simulations are not feasible with the “brute-force” approach of using intermediate phase-space files as input to the chamber response simulations. Hence, the main program of the BEAMnrc was modified to

Figure 3.2: $D(E)/K_{\text{air}}(E)$ vs incident energy for the different build-up caps and mini-phantoms, calculated for a horizontally oriented chamber placed on the beam axis.

Figure 3.3: Cross section of the vertically oriented ion chamber with a build-up cap in the photon beam. The chamber is positioned on the beam axis and off-axis.

consist of three separate subroutines: an initialization subroutine, a shower loop subroutine and a subroutine for analyzing and reporting the results of the simulation. In the initialization subroutine the input file is read and geometry and cross section data are initialized. In the shower loop subroutine a given number of particles as specified in the input file are simulated by calling the EGSnrc **SHOWER** subroutine the specified number of times. The new BEAMnrc main program is now very short consisting of subsequent calls to the three subroutines. An alternative shower loop subroutine was then developed, which repeatedly calls **SHOWER** until at least one particle crossing a specified scoring plane is recorded in a “particle container” (a set of arrays to store particle positions, directions, energies, charges and statistical weights). To record particles into the container the regular BEAMnrc macro for writing particles into a phase space file was replaced by a macro which stores the particle parameters into the container. With these changes, a BEAMnrc user code can be compiled into a stand-alone executable program using the very small main program, the three subroutines mentioned above and the original phase-space writing macro, or into a shared library (also known as dynamic shared object, DSO, in the Linux/Unix world or dynamically linkable library, DLL, in the Windows world) using the initialization and analysis subroutines, the new shower loop subroutine and the new macro for recording particles into the container from the same code base. To facilitate the use of a BEAMnrc user code shared library as a particle source for other EGSnrc user codes, a new source type for the standard set of NRC user codes was developed. This new source takes as input the BEAMnrc user code name, the input file specifying geometry and transport parameters for the treatment head simulation, and a PEGS4 file containing the media cross section data needed for the BEAMnrc simulation. The source then dynamically loads the shared library into memory, resolves the addresses of the three subroutines and calls the BEAMnrc initialization subroutine passing the

input file and PEGS4 file as arguments. At run time, each time the source is asked to deliver a particle it calls the new shower loop BEAMnrc subroutine which returns the top particle in the container along with the history number of the incident electron from which the particle originated and decreases the container counter by one, or, if there are no particles in the container, simulates particles through the treatment head until recording at least one particle in the container. In this way any BEAMnrc user code can be used as a source to any other or the EGSnrc RZ user codes without the need to recompile the user code each time a different linear accelerator is simulated.

The CAVRZnrc user code was used together with the new BEAMnrc source to perform the chamber response simulations for the vertical orientation of the chamber and also for a few cases with a horizontal chamber orientation to confirm that the calculation technique described in the previous section is accurate. Within one full simulation the CPU time used for CAVRZnrc calculation is about three times higher than the same for BEAMnrc calculation. Note that in all simulations using the new BEAMnrc source all particles are taken into account, including contamination electrons. One disadvantage of the new technique is that the treatment head simulation is repeated again and again for each chamber position. Nevertheless, it is still substantially more efficient than the “brute-force” approach of using intermediate phase-space files.

3.2 Calculation of air-kerma profiles

For a photon beam in air, the collision kerma K_{air} at a given point away from the source is proportional to the photon fluence $\Phi(E, x)$ as follows:

$$K_{\text{air}}(x) = \int dE \Phi(E, x) E \left(\frac{\mu_{\text{en}}(E)}{\rho} \right)_{\text{air}}, \quad (3.8)$$

where $(\mu_{\text{en}}(E)/\rho)_{\text{air}}$ is the mass energy absorption coefficient in air at photon energy E . Using the same assumptions as in (3.1.A), we can approximate equation (3.8) by

$$K_{\text{air}}(x) = \frac{1}{A} \sum_i \frac{w_i}{|\cos \theta_i|} E_i \left(\frac{\mu_{\text{en}}(E_i)}{\rho} \right)_{\text{air}}. \quad (3.9)$$

Here A is the area around position x used to accumulate the result for $K_{\text{air}}(x)$ and the summation is over all particles crossing the area A . Thus, in our calculations the collision air-kerma profiles $K_{\text{air}}(x)$ were computed on the fly within the BEAM simulations by scoring the mass energy absorption coefficient times energy and weight for each particle passing through a scoring region. The mass energy absorption coefficients of air for each photon energy were interpolated from the tables of Hubbell and Seltzer.⁴⁸

3.3 Head-scatter factor calculations

As discussed before (see section 2.3), the head-scatter factor S_c is determined as the ratio of the dose to the air cavity of the chamber measured for an arbitrary field to the dose measured at the reference collimator setting, usually for a nominal field of 10x10 cm² and the nominal SSD of 100 cm for linacs:

$$S_c = D(r)/D(10), \quad (3.10)$$

where $D(r)$ is the dose, deposited to the air cavity of the chamber in an arbitrary field of size r and $D(10)$ is the dose measured in the reference field of $10 \times 10 \text{ cm}^2$. Therefore, S_c is normalized to 1 for the nominal field of $10 \times 10 \text{ cm}^2$.

MC calculations of the head-scatter factors were performed for the 6 and 10 MV beams used in the experiments. The dose deposited to the cavity of a horizontally oriented chamber was calculated for each square field in the range from $7 \times 7 \text{ cm}^2$ to $40 \times 40 \text{ cm}^2$ when the chamber was positioned on the central beam axis. The hevimet and brass build-up caps and the smaller PMMA mini-phantom were used in the simulations, as was done in the measurements.

For head-scatter factor calculations the user code CAVRZnrc was employed. The new particle source type 23, developed for the simulations of the vertically oriented chamber, was used for this purpose. To simulate the treatment head with different collimator setting, corresponding to the different field sizes, the BEAMnrc simulation was run with input files specifying geometry for each setting. Each dose, computed to a statistical uncertainty of 0.1%, was normalized to the dose, calculated for the $10 \times 10 \text{ cm}^2$ field at the nominal SSD of 100 cm.

Chapter 4

Results and discussion

4.1 Off-axis ratios

As was mentioned before, in-air OAR profiles are very sensitive to the energy and spot size of the incident electron beam. Fig. 4.1 shows calculated OAR profiles for a horizontally oriented ion chamber with the hevimet build-up cap and the larger PMMA mini-phantom for different incident energies and the same spot size radius of 0.05 cm. Fig. 4.2 shows OAR profiles calculated for different spot size values and the same energy of the incident beam of 9.4 MeV.

As can be seen, changing the incident energy and spot size have different effects on the shape of the calculated beam profile and therefore, in order to reproduce the measured profiles, it is necessary to find the unique energy/spot size combination for the incident electron beam. To accomplish this task, in-air profiles were generated in the intervals of incident energies 5 - 6.5 MeV, 8.5 - 10.5 MeV and 16 - 25 MeV, varying the spot size from 0 to 0.25 cm. The best fit for the 6 MV measurements

Figure 4.1: Sensitivity of the in-air profiles to the energy of incident electron beam. First graph shows OARs for a hevimet build-up cap, the lower graph is for the larger PMMA mini-phantom. The chamber is oriented horizontally. Incident beam energies range from 8.5 MeV to 10.5 MeV, the spot size is 0.05 cm.

Figure 4.2: Sensitivity of the in-air profiles to the spot size of incident electron beam. The upper graph is for a hevimet build-up cap, the lower one shows OARs for the larger PMMA mini-phantom. The chamber is oriented horizontally. Incident energy is 9.4 MeV, spot size values range from 0.05 cm to 0.25 cm.

was found when using 5.75 MeV incident energy and 0.15 cm spot size, and for the 10 MV measurements - 9.4 MeV and 0.05 cm respectively. It was impossible to obtain a good match with the experiment for the 25 MV beam by simply varying the incident electron energy and spot size. Therefore, particle source 19, parallel circular beam with a 2-D Gaussian X-Y distribution, had to be modified in the BEAMnrc code to permit the simulation of a Gaussian spread of the incident electron direction in addition to a Gaussian spread of the initial electron position. With the width of the angular distribution as an additional free parameter in the simulation it was possible to reproduce the OAR profiles using incident electron energies between 16.7 MeV and 19 MeV. Based on estimates of the incident electron energy and bending magnet settings in electron beams (see below), we used the 19 MeV results for all calculations presented here. The corresponding spot size and angular width are 0.19 cm and 1.15 degrees respectively. In addition to the use of angular spread of the electrons incident on the target, there is another difference between the lower energy beams and the 25 MV beam. Unlike the 6 and 10 MV beams, where it was possible to reproduce the measured profiles using the leading term of the bremsstrahlung angular distribution (this is the default setting in BEAMnrc), the full bremsstrahlung angular distribution according to Eq. 2BS of Ref. 39 had to be used for the 25 MV beam.

To assess how realistic the incident electron energies are, independent estimates were derived from electron beam depth-dose data and current settings for the linac bending magnet as follows. R_{50} measurements in electron beams of nominal energies 4, 8, 12, 18 and 22 MeV were used to derive estimates of the mean electron energy incident on the water surface $\overline{E_o}$ using the relation given in ICRU (International Commission on Radiation Units) Report 35⁴⁹

$$\overline{E_o} = 2.33R_{50} . \quad (4.1)$$

Details of the components in the treatment head (monitor chamber, scattering foils, air, etc.) and stopping power data from ICRU Report 37⁵⁰ were used to estimate the energy lost by the electrons as they are transported to the phantom surface and thus derive the electron energy at the vacuum exit window of the accelerator E_a . The relationship between E_a and the $\overline{E}_o$ is given by the approximate formula:

$$\overline{E}_o = E_a - \sum_n (\Delta E)_{tot,n} , \quad (4.2)$$

where $(\Delta E)_{tot,n}$ is the mean total energy loss in a layer n of material being traversed. This approximate technique is not as accurate as a full MC simulation but provides an estimate, which is typically within 0.5 MeV as shown by Ding *et al.*⁵¹

The Elekta linac uses a "slalom" bending magnet with a bending angle of 112.5 degrees. The linac control system provides values for the bending magnet settings for each beam energy and by comparing these settings for photon and electron beams one can infer the electron energy incident on the bremsstrahlung target for the three photon energies. The estimates obtained in this way are shown in column 2 of Table 4.1. The uncertainty given in Table 4.1 is the combination of the uncertainty in the energy-range relation, determination of energy losses in the treatment head and interpolation of the bending magnet settings. For comparison the values obtained from the matching of experimental and simulated OAR profiles are shown in column 3. The good agreement between the two independent methods increases our confidence in the results from the MC simulations.

Figures 4.3-4.5 show results of MC simulations in comparison with the experimental OAR profiles for a horizontally oriented ion chamber in the 6, 10 and 25 MV beam respectively. The lines correspond to the experimentally measured in-air profiles and the symbols show calculated OARs. All simulations were performed using the technique discussed in section 3.1.A, except for the region close to the edge of the

Table 4.1: Elekta Precise linac electron energy for photon beams.

E_{nom} , MV	E_a , MeV (estimated)	E_a , MeV (simulation)
6	5.7 ± 0.4	5.75
10	9.0 ± 0.4	9.4
25	19.9 ± 0.7	19.0

field when using the larger PMMA mini-phantom. As it was suspected earlier, the accuracy of the method here is reduced because part of the mini-phantom is outside of the field, however the tabulated response functions were calculated for a fully irradiated chamber and a mini-phantom. Results of the calculations for build-up caps are not affected due to their smaller dimensions. Thus, for the larger mini-phantom in the region close to the edge of the field we need to use the full simulation method, employed for a vertically oriented chamber (see section 3.1.B). Results of the full simulations for the large mini-phantom at distances greater than 15.5 cm from the central axis are plotted as open triangles in Fig. 4.3, in comparison with OARs computed using the tables (filled triangles). As it can be seen, combination of the computational techniques allows us to obtain a good agreement with the measurements done with the large mini-phantom in a 6 MV beam. For 10 and 25 MV beams results of the full simulations and the calculations using the tables for a large PMMA mini-phantom in a region close to the field edge give very similar results, as it is demonstrated in Fig. 4.4. Right now we don't have an explanation for such a different behavior depending on the beam energy.

In the simulation for a 25 MV beam the small mini-phantom is not included (Fig. 4.5), as well as it was not used in the measurements at this energy, because its thickness is not sufficient to give maximum dose build-up at high energy.

All presented off-axis ratios agree very well with the measured ones: for most points the agreement is within the statistical uncertainty of the MC simulations (0.3% or better) for all investigated build-up caps and mini-phantoms in all photon beams.

For a vertically oriented chamber we used the same incident energy and spot size values, obtained by fitting the experimental data for a horizontally oriented chamber, because measurements were performed in the same beams. Fig. 4.6 shows results of MC simulations and measurements for a vertically oriented ion chamber in the 6 MV photon beam for different build-up caps. Here the agreement is not as good as for the horizontally oriented chamber. Nevertheless, the simulations reproduce the trend in the measurements and the deviations generally do not exceed 1%. Differences for the higher energy beams are even larger. This can be explained in terms of the geometry approximation implemented in CAVRZnrc. When the chamber is oriented vertically, details of the tip of the chamber and build-up cap are much more important and this is the reason why in this case the agreement with the experimental data is less satisfactory. Both approaches in our build-up cap approximations (see section 3.1.A) are not sufficient in this case. If the conical tip is modeled by a cylinder with the same height, the photon attenuation is correctly reproduced but the contributions due to scattered photons are overestimated due to the 3 times larger volume. If the conical tip is modeled with a cylinder with the same volume, dose contributions from scattered radiation are correctly reproduced but the photon attenuation is underestimated due to the roughly 3 times smaller thickness. Since the beam spectrum changes with distance from the central axis, such effects will vary and therefore make

Figure 4.3: OARs as a function of off-axis distance for horizontally oriented ion chamber in a 6 MV beam. The lines show experimentally measured profiles compared to Monte Carlo calculations shown as the symbols. For the larger mini-phantom at a distance greater than 15 cm from the central axis, results of the full simulations are also shown. Energy and spot size of the incident beam in MC calculations are 5.75 MV and 0.15 cm respectively.

Figure 4.4: Same as Figure 4.3, for a horizontally oriented ion chamber in a 10 MV beam. Energy and spot size of the incident beam in MC calculations are 9.4 MeV and 0.05 cm respectively.

Figure 4.5: Same as Figure 4.3, for a horizontally oriented ion chamber in a 25 MV beam. Incident energy is 19 MeV, spot size is 0.19 cm and the width of the Gaussian angular distribution of the incident electron beam is 1.15 degrees.

the calculated cavity dose as a function of off-axis distance unreliable.

4.2 Collision air-kerma profiles

It was shown in the previous section that the calculated in-air profiles are in good agreement with the experimentally measured profiles for different build-up caps. This implies that the simulation properly takes into account the effect of the ion chamber and build-up cap on the dose deposited in the chamber cavity. The difference between a calculated collision air-kerma profile and a calculated OAR profile simulated with a given build-up cap will therefore represent the difference between collision air-kerma and a measured OAR profile using this build-up cap. Fig. 4.7 shows collision air-kerma and OAR profiles calculated for a horizontally oriented ion chamber inserted in a build-up cap made of the different materials for a 6 MV beam. The energy and spot size of the incident electron beams are the same as was determined in the previous section. The difference between the air-kerma and OARs becomes significant (over 1%) at about 7 cm off-axis and reaches its maximum close to the edge of the field. OARs for hevimet show the largest difference (about 5-6%) from kerma in air. For brass the difference is about 3-4% and for PMMA mini-phantoms the difference between OARs and air kerma is within 1% for the small one and about 2% for the large mini-phantom. The same trend is shown in Fig. 4.8 for the 10 MV beam: the closest to the actual kerma profile is the in-air profile calculated for PMMA mini-phantoms.

Fig. 4.9 shows air-kerma and OAR profiles for the 25 MV beam. The difference is up to 2.5% for the small PMMA mini-phantom, 8% for brass and 10% for hevimet. The larger differences between air-kerma and the OARs measured with build-up caps and the small PMMA mini-phantom compared to the lower energy beams can be

Figure 4.6: Measured and calculated OAR profiles for a vertically oriented ion chamber in a 6 MV beam for the different build-up caps and the smaller mini-phantom.

Figure 4.7: Calculated collision air-kerma and OAR profiles for a horizontally oriented chamber in a 6 MV beam, shown for the different build-up caps and PMMA mini-phantoms.

Figure 4.8: Same as Figure 4.7, for a 10 MV beam.

Figure 4.9: Calculated collision air-kerma and OAR profiles for a horizontally oriented chamber in a 25 MV beam, shown for the different build-up caps and the larger mini-phantom.

easily understood by consulting Fig. 3.2, which shows the energy dependence of the chamber response per unit air-kerma for different build-up caps. It can be noted that at higher energies the hevimet and brass responses have much steeper slope and response of the small PMMA mini-phantom declines due to insufficient build-up thickness. Thus, one can expect more significant difference between air-kerma and OAR for high energy beams. Off-axis ratios for a large mini-phantom and air-kerma profile give the same values within the statistical uncertainties.

The comparisons shown in Figs. 4.7-4.9 demonstrate that using a PMMA mini-phantom yields a profile that is much closer to the actual air-kerma without any significant loss in spatial resolution. Based on those results, the recommended method for in-air measurements is an ion chamber inserted in a low- Z material mini-phantom.

4.3 Head-scatter factors

Head-scatter factor measurements discussed in Chapter 2 show a 1% difference for large fields in a 10 MV beam and a less significant variation (about 0.5%) in a 6 MV beam when using hevimet build-up cap and the smaller PMMA mini-phantom. Head-scatter factors measured with the brass build-up cap gave intermediate values (Fig. 2.4).

Fig. 4.10 shows results of the Monte Carlo simulation for both investigated photon beams, using the hevimet and brass build-up caps and the small PMMA mini-phantom as in the experiments. Calculated head-scatter factors have the same trend as the measured ones: a difference of 1% between hevimet build-up cap and PMMA mini-phantom for large fields (over $15 \times 15 \text{ cm}^2$) in a 10 MV beam and smaller discrepancy (about 0.5%) for a 6 MV beam with the intermediate values for the brass

Figure 4.10: Head-scatter factors calculated with MC simulations for different build-up caps and the smaller mini-phantom in a 6 MV (upper graph) and in a 10 MV (lower graph) photon beam from the Elekta linac.

build-up cap. For large fields S_c is greater for the mini-phantom than for the hevimet. For the small field ($7 \times 7 \text{ cm}^2$), on the contrary head-scatter factors measured and calculated with the hevimet build-up cap are greater than that for the PMMA mini-phantom. This effect is due to the size of the mini-phantom which doesn't fit with this small field. The difference in the results for 6 and 10 MV can be explained in terms of the energy dependence of the ion chamber response when using different build-up caps (Fig. 3.2): with the increase of the photon energy the responses for hevimet and brass become more energy dependent than for PMMA. Hence, the discrepancy in the dose measurements is greater at higher energies, as it was discussed in the previous sections.

Computed and measured head-scatter factors are compared in Figs. 4.11 and 4.12 for each build-up cap and a mini-phantom in both investigated photon beams. The results demonstrate good agreement within the uncertainties between the measurements and the calculations. However, there is the same tendency in all graphs showing the calculated head-scatter factors to have slightly higher values than the measured ones for large fields and lower values for the $7 \times 7 \text{ cm}^2$ field. A possible explanation for trend is the fact that the simulation doesn't model some additional material presented in the experiment, for instance aluminum tubes supporting the mini-phantom as it is shown in Fig. 2.3, which could affect the results. Such additional scatter contribution will be approximately the same for all field sizes reducing S_c for larger fields and increasing S_c for small fields.

Figure 4.11a

Figure 4.11b

Figure 4.11c

Figure 4.11: Measured and calculated head-scatter factors at 6 MV for different build-up caps and a mini-phantom: a - hevimet; b - brass; c - PMMA.

Figure 4.12a

Figure 4.12b

Figure 4.12c

Figure 4.12: Measured and calculated head-scatter factors at 10 MV for different build-up caps and a mini-phantom: a - hevimet; b - brass; c - PMMA.

Chapter 5

Conclusions

This thesis investigates the influence of ion chamber response on in-air profile and head-scatter factor measurements in megavoltage photon beams using MC simulations with the EGSnrc system. Two new techniques for the calculation of OARs when an ion chamber is oriented horizontally or vertically are presented. For a horizontally oriented chamber pre-calculated tables of the ion chamber response as a function of photon energy can be used to compute on the fly the dose deposited in the chamber cavity when the chamber is inserted in a build-up cap and positioned at a certain distance from the axis. For a vertically oriented chamber a modified BEAMnrc version that can be compiled into a shared library serves as a particle source for other EGSnrc user codes. A new source type for the standard set of NRC user codes was developed for this purpose. With these changes the OAR calculations can be performed on the fly without intermediate phase-space file generation. The new particle source is also used in CAVRZnrc simulations to calculate the head-scatter factors.

Results of MC simulations are compared with measurements obtained in the megavoltage photon beams from the Elekta Precise linear accelerator at IRS/INMS,

NRC. Off-axis ratios were measured in the 6, 10 and 25 MV beams, using a graphite-walled NE2571 Farmer type ionization chamber inserted in a build-up cap or mini-phantom. Build-up caps made of hevimet and brass were investigated along with two PMMA mini-phantoms of different sizes. For the head-scatter factor measurements the same build-up caps and with the smaller mini-phantom were used in the 6 and 10 MV photon beams.

Off-axis ratios are extremely sensitive to the incident electron beam energy and spot size. Once the appropriate energy-spot size combination is used in the MC simulations, the calculated and measured off-axis ratios are shown to agree within the experimental and statistical uncertainty (0.3%) for a horizontally oriented chamber in all investigated photon beams for each build-up cap and mini-phantom. This indicates that the simulation properly takes into account the effect of the ion chamber and build-up cap on the dose deposited in the chamber cavity. For a vertically oriented ion chamber in a 6 MV beam the simulations reproduce the trend in the measurements and the deviations generally do not exceed 1%. This less satisfactory agreement with the experimental data can be explained in terms of the limitations of the chamber shape approximation within the CAVRZnrc user code.

The comparison of the calculated air-kerma and OAR profiles for high- Z material build-up caps and low- Z mini-phantoms shows a difference of 3-6% between air-kerma and in-air profiles for the build-up caps and 0.5-2% for the mini-phantoms at 6 and 10 MV. For a 25 MV beam the differences reach 10% for hevimet and 8% for brass and became negligible for a larger mini-phantom. This is due to the fact that at higher energies the hevimet and brass responses are much more energy dependent than the PMMA, as can be seen in Fig. 3.2.

Head-scatter factor simulations were performed in the 6 and 10 MV photon

beams for square fields with the side in a range from 7 cm to 40 cm. Both calculations and experiments demonstrate 1% difference between head-scatter factors obtained with hevimet build-up cap and PMMA mini-phantom for large fields (over $15 \times 15 \text{ cm}^2$) in a 10 MV beam and about 0.5% difference in a 6 MV beam, while using brass build-up cap gives intermediate values. Comparison of the calculated and measured head-scatter factors for each build-up cap and a mini-phantom demonstrates good agreement within 0.1% uncertainties for both investigated beams.

This study confirms the conclusions of Sheikh-Bagheri and Rogers⁷ that in-air OAR profiles are very useful in the MC beam commissioning process due to their sensitivity to the incident electron energy and spot size. However, the varying response of the chamber inserted in a build-up cap with distance from the central axis must be taken into account. Based on the results of this investigation, the low density mini-phantoms are recommended over high- Z material build-up caps as a method of a choice for off-axis ratio and head-scatter factor measurements in air.

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