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Linac Head Scatter Factor for Asymmetric Radiation Field

by

Mazen Ahmed Soubra, MSc.

A thesis submitted to the
Faculty of Graduate Studies and Research
in partial fulfillment of the requirements
for the degree of

Doctor of Philosophy

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Mazen Ahmed Soubra, Msc.

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

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Abstract

The head scatter factor, S_h , is an important dosimetric quantity used in radiation therapy dose calculation. It is empirically determined and its field size dependence reflects changes in photon scatter from components in the linac treatment head. In this work a detailed study of the physical factors influencing the determination of S_h was performed with particular attention given to asymmetric field geometries.

Ionization measurements for 6 and 18 MV photon beams were made to examine the factors which determine S_h . These include: phantom size and material, collimator backscatter, non-lateral electronic equilibrium (LEE) conditions, electron contamination, collimator-exchange, photon energy, flattening filter and off-axis distance (OAD). Results indicated that **LEE** is not required for S_h measurements if electron contamination is minimized. Brass caps or polystyrene miniphantoms can both be used in S_h measurements provided the phantom thickness is large enough to stop contaminant electrons. Backscatter radiation effects into the monitor chamber were found to be negligible for the Siemens linac. It was found that the presence and shape of the flattening filter had a significant effect on the empirically determined value of S_h , was also shown to be a function of OAD, particularly for small fields. For fields larger than 12 x 12 cm² S_h was independent of OAD. A flattening filter mass model was introduced to explain qualitatively the above results.

A detailed Monte Carlo simulation of the Siemens KD2 linac head in 6 MV mode was performed to investigate the sources of head scatter which contribute to the measured S_h . The simulated head components include the flattening filter, the electron beam stopper, the primary collimator, the photon monitor chamber and the secondary collimators. The simulations showed that the scatter from the head of the Siemens linac is a complex function of the head components. On the central axis the flattening filter played the dominant role in the contributing to scatter. However this role was significantly reduced off-axis and other head components, such as the electron beam stopper and the primary collimator, became more important. The role of the mirror and ion chamber was relatively minor. Scatter from the secondary collimators was shown to be a function of the field size and the position of the collimators in the treatment head. They were also found to play a dual role, both as a scatter source and as an attenuator for scatter produced upstream in the linac head.

A closed form model, based on the work of Yu and Slobada, was developed to estimate head scatter factors for on- and off-axis asymmetric fields. The model requires three parameters to fit the measured data. The first, a constant c , has a physical significance and is independent of energy and off-axis distance. The second, g , shows a small variation with the energy and OAD while the third parameter, the primary-to-scatter ratio, is strongly dependent on energy and off-axis distance. Comparison of S_h , predicted by the model, to measurement for a large range of symmetric and asymmetric fields showed excellent agreement. A maximum of 0.7% discrepancy was observed at 12 cm OAD.

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I wish to thank my Supervisor, Lee Gerig, for his advice and patience, Peter Raaphorst for his encouragement and support, my colleagues Doug Salhani, Janos Szanto and Alan Li for their critical analysis. I also wish to thank Dave Rogers of the NRCC for permission to use the ACCEL Monte Carlo Code and my Ph.D., Advisory Committee for their guidance. My appreciation goes to Ottawa Cancer Treatment & Research Foundation, for allowing me to use their facilities.

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List of Abbreviations

LEE	Lateral electronic equilibrium
OAD	Off-axis distance
S_h	Head scatter factor
S_p	Phantom scatter Factor
$S_{hp} = S_p * S_h$	Total scatter factor
ROF	Relative output factor
SAD	Source to axis distance
TAR	Tissue air ratio
TPR	Tissue phantom ratio
OAR	Off-axis ratio
BSR	Backscatter radiation
Kerma	Kinetic energy transferred by photons to charge particles per unit Mass
SSD	Source to skin distance
CPE	Charge particle equilibrium
P/S	Primary-to-scatter ratio

Chapter 1 Introduction

1.1 Overview

Medical linear accelerators (linacs) have been used for the last three decades in the treatment of cancer. A recent major development in commercially available linacs has been the incorporation of independently movable or asymmetric jaws into the collimation system which defines the useful treatment field. Each field defining jaw is approximately 8 cm thick and is made of a high atomic number material (Tungsten, Uranium (depleted) etc.). Historically¹ only rectangular fields, which are symmetric about the collimator rotation axis (see figure 1.1a), have been available since the opposing jaws were restricted to symmetric motion. In modern linacs¹ each jaw can be driven independently and their inward movement is not limited to the x-ray beam central axis but can proceed across the axis towards the opposing edge of the beam. This results in asymmetric positioning of the field defining jaws with respect to the nominal beam central axis (see figure 1.1b).

There are many clinical situations where the increased flexibility of independent (asymmetric) jaw motion results in the ability to deliver superior dose distributions.

Examples of such clinical use include:

1. Half block breast tangential treatment fields which eliminate beam divergence resulting in a reduced dose to the lung and simplified field matching.

Figure 1.1 Symmetric and Asymmetric Collimation

- (a) A typical symmetric field defining system consists of two pairs of movable jaws: the upper and the lower jaws. The jaws are driven in pairs and their motion is symmetric about the beam central axis. This causes the treatment field centre to be coincident with the central axis
- (b) An asymmetric field defining system consists of two pair of movable jaws where each jaw can be driven independently and it's inward movement is not limited to the central axis. This can result in asymmetric positioning of the jaws and the treatment field centre to be displaced from the nominal beam central axis.

2. The post axilla boost field when treating full isocentric breast allowing the use of a single isocentre thus reducing set-up time and errors.
3. In arc therapy, asymmetric collimation allows beam orientations which deliver a tumouricidal dose to a volume which surrounds a critical organ^{1,2,3} while ensuring minimum dose delivery to the organ at risk.

1.2 The Problem

The physical problem of clinical significance arising from the use of asymmetric collimation is the determination of the absorbed dose (rate) at a point in a target. The linear accelerator output, which is defined as the dose per monitor unit (cGy/mu) at a point in the patient, is a function of many factors including the following:

1. Scattered radiation from the treatment head
2. Radiation scattered within the patient
3. Inverse square law
4. Backscatter radiation from the collimator jaws to the linac ion chamber (monitor chamber)
5. Incident photon energy fluence distribution at the patient surface (i.e. Primary open beam profile shape)
6. Electron disequilibrium effects
7. Beam attenuation

The presently accepted method for calculating linear accelerator output (cGy/mu) is discussed by Khan⁴ (see chapter 2). This approach separates the total scatter factor ($S_{h,p}$) into a phantom scatter factor (S_p) and a head scatter factor (S_h). The phantom scatter term arises primarily from Compton interactions in the irradiated medium. This is well understood and routinely handled with relative accuracy in the currently available computerized photon dose calculations^{5,6,7}. Many authors have attributed differences in the total scatter factor between different linear accelerators of similar nominal energy to be the result of head scatter effects^{8,9,10}, including the backscatter^{11,12,13} to the beam monitor chamber.

Head scatter includes scatter from the components of the treatment head which are in the incident beam path and the collimator backscatter into the monitor chamber (see chapter 2). The contributions from these two processes (i.e. forward scatter and backscatter to monitor chamber) are integrated into the single quantity head scatter factor S_h , where S_h is defined as the ratio of output [cGy/mu] (exposure rate, dose rate in free space or energy fluence)⁴ for a given collimator field size to that for a reference collimator field size. For symmetric fields, S_h is measured in “air” along the beam central axis at isocenter. Conventionally tables of S_h values are prepared from measured data. This table is very large, usually consisting of more than 200 points in order to account for collimator exchange effects in which S_h for a field size $X \times Y$ is not the same as S_h for a field size $Y \times X$. This approach is not practical for asymmetrically collimated fields due

to the extremely large number of field arrangements which can be produced by the independently movable jaws. The issue then becomes; how can S_h be determined for any combination of jaw settings?

This clinical problem is best addressed by understanding the physical nature of head scatter and then by developing a model to predict S_h for asymmetric fields as part of the routine dosimetry calculations.

1.3 This Work

This work examines the many physical parameters which influence S_h . The objective is to predict the head scatter factor for all asymmetric x-ray fields defined at any off axis distance.

The physical parameters affecting S_h values have been investigated both experimentally and using Monte Carlo simulations. The experimental studies include:

1. The effects of electron contamination and lateral electron disequilibrium on the measurement of S_h .
2. The effect of phantom dimension and atomic number on the "in-air" measurements of S_h .
3. The contribution of backscatter radiation (from the collimators to the linac ion chamber) to the value of S_h .
4. The effect of photon energy, field size and off axis distance on the magnitude of S_h .

5. The role of scatter from the photon beam flattening filter.

The Monte Carlo studies include the following:

1. An examination of lateral electronic equilibrium for clinical photon energies and its influence on the determination of S_h .
2. The relative importance of scatter from the individual components of the accelerator head (e.g. electron beam stopper, primary collimator, flattening filter, monitor chamber, mirror and collimator jaws) for a Siemen's Mevatron linac head. The primary and total energy fluence spectra produced by 6.0, 7.0 and 7.5 MeV electron beams incident on the bremsstrahlung target have been scored for individual and grouped head components.

The results of these experimental and Monte Carlo investigations have then been utilized in the development of a model for predicting S_h values for any asymmetric field whose center is located at any position in the X-ray beam. This model is discussed in detail in chapter 5.0

1.4 Thesis Organization

Chapter 2 contains background to the current work including a detailed literature review of the relevant reports which deal with the methods of S_h evaluation and measurement. Chapter 3 presents the materials and methods employed in the experimental and Monte Carlo studies. Chapter 4 presents the results of the Monte Carlo

and experimental studies. Chapter 5 describes the model, its formalism as developed in this work for predicting S_h values and the results of comparison between estimated and measured data. Chapter 6 discusses all the results obtained in this work. In chapter 7 the scope for further work is summarized.

Chapter 2 Background

Historically, all field size dependent photon scatter has been amalgamated into a single term, the relative output factor (*ROF*). This methodology results in dose errors for treatments at extended distance or with shielding as described in section 2.2. Holt et al¹⁴ named the *ROF* as the total scatter factor ($S_{h,p}$) and proposed this quantity to be thought of as the multiplicative effect of two factors S_h and S_p which account for head and phantom scatter respectively. Khan et al⁸ extended this proposal and suggested simple methods of determining these two factors. This approach provides relatively accurate dosimetry for symmetric fields when the tumour target dose is specified on the beam central axis and the off-axis doses are obtained from isodose distributions. However with the introduction of asymmetrically collimated fields the dose calculation point moves off-axis and one must consider changes in the head scatter, phantom scatter, and beam quality^{15,16} as a function of the off-axis distance. These changes in beam quality and head scatter arise due to the presence of the beam flattening filter which causes greater beam hardening (different energy spectrum) close to the central axis than at the periphery of the beam. Under these conditions the approach of Khan becomes inaccurate.

In the following sections the principal terms used in dose calculation are summarized and the methods and techniques for measuring and evaluating the various parameters are reviewed. Reports of other workers are surveyed and the relative contribution of the various head components to scatter and their influence on S_h are reviewed.

2.1 Symmetric Field Dose Calculation Parameters

A commonly accepted method¹⁷ for calculating the dose delivered to a point in a patient from symmetric fields is based on the separation of total dose into primary and scatter⁴.

The primary dose is that deposited by the photons which are emitted from the bremsstrahlung target and have not experienced scatter on their way to the interaction site. The scattered dose is dose which is deposited by photons scattered within the phantom (patient) or the treatment head. The practical difficulty which arises in such a dosimetry protocol is to determine how much of the dose is due only to primary beam, excluding both head and phantom scatter. To overcome this problem for megavoltage x-ray beams, Khan et al⁸ have taken a slightly different approach in which they proposed a quantity referred to as the *effective primary dose*. This is defined as the dose due to primary photons plus head scatter. In this approach it is possible to separate total dose into phantom scatter and effective primary dose. The effective primary dose is similar in concept to the *absorbed dose in free space*¹⁸ which applies to photon beam energies less than 4 MV. The various dosimetric quantities used in dose calculations are discussed below.

2.1.1 Total Scatter Factor

The total scatter factor ($S_{h,p}$) is defined⁴ as the dose (rate) at a reference depth in a phantom for a given field size divided by the dose (rate) at the same point and depth for

the reference field size (see figure 2.1b). The measurement point is usually at the source to axis distance (SAD) of the specific therapy unit. Field size dependent changes in $S_{h,p}$ represent the change in the amount of both head and phantom scatter with field size. To eliminate the influence of contaminant secondary electrons, produced by materials intercepting the path of the photon beam, $S_{h,p}$ measurements are performed at depths greater than the range of most charged particles incident on the phantom. In this work the measurement depth is chosen in accordance with the recommendations of the TG21 dosimetry protocol¹⁹.

2.1.2 Head Scatter Factor

S_h may be defined⁸ as the ratio of the effective primary dose (rate) for a given collimator field size to that for a reference field size. Other workers have interpreted S_h as the ratio of either the total incident photon fluence^{20,21} or the total incident energy fluence²² at a point for one field size with respect to a reference field size. Irrespective of the conceptual differences there is a common acceptance that S_h is a function of collimator jaw opening and can be measured in-air by an ionization chamber with sufficient buildup material as illustrated in figure 2.1a). In this regard there remain as yet unresolved issues, one of which is addressed in this study, specifically the size and type of material used for buildup (see details in section 2.4). For the purpose of this work S_h is defined, as stated in the introduction, as the ratio of the measured output for a given

field size to that for a reference field size, where the field dimensions are those defined by the collimator jaws at 100 cm SAD.

2.1.3 Phantom Scatter Factor

The phantom scatter factor accounts for the dose at a point due to field size dependent scatter radiation originating in the phantom. S_p is defined⁴ as the ratio of the dose rate for a given field size to the dose rate at the same depth for a reference field size with **the same collimator opening** (see figure 2.2). S_p is difficult to measure directly but can be calculated by removing S_h from the total $S_{h,p}$, such that

$$S_p = \frac{S_{h,p}}{S_h} \quad (2.1)$$

where $S_{h,p}$ and S_p are defined at the reference depth.

2.1.4 Tissue Phantom Ratio

At energies greater than ^{60}Co , the buildup cap used for ionization measurement in-air becomes large enough to begin acting as a phantom. As such, tissue air ratio (TAR) is extremely difficult to determine for megavoltage x-rays. In its place, the concept of tissue phantom ratio (TPR) was first introduced by Karzmark et al²³ in an attempt to retain the properties of TAR but to limit the measurements to phantom rather than the required measurements in phantom and in-air. The TPR is defined as the ratio of the dose (D_d) for a field of side r at a given point in phantom to the dose (D_{ref}) at the same

Figure 2.1 Experimental Arrangement for Measuring S_h and $S_{h,p}$

Experimental arrangement for measuring S_h (a) and $S_{h,p}$ (b). In diagram (a) an ionization chamber with buildup cap is placed in air to measure a field output. In diagram (b) an ionization chamber is placed in a water phantom at a reference depth to measure field output. The chamber readings are normalized to the reference field. The SAD and reference fields in both diagrams are equal.

Figure 2.2 Definition of S_p

This diagram illustrates the definition of S_p : Dose in a phantom at a reference depth for a given field size is normalized to the dose at the same depth for a reference field with the same collimator opening.

Figure 2.3 Tissue Phantom Ratio (TPR)

This diagram illustrates the definition of tissue phantom ratio (TPR).

$TPR(d,r) = D_d / D_{ref}$, where D_d is the dose at depth d for a field of side r and D_{ref} is the dose at a fixed reference depth d_{ref} .

point at a fixed reference depth as is illustrated in figure 2.3. The *TPR* accounts for both attenuation and the scatter change with depth (d) in the phantom due to variation in the irradiated volume above the reference point. *TPR* is a general function that may be normalized to any reference depth. If the depth of maximum dose is chosen as the reference, then *TPR* is known as tissue maximum ratio (*TMR*). There is no universal agreement on the correct reference depth to be used, however the values recommended by the TG21¹⁹ protocol for dose measurements were used in this work.

2.2 Dose Calculations in Symmetric Fields

The most common formalism for calculating the dose rate $\dot{D}_{x,y}$ (Gy/mu) at a point on the central axis of a symmetric high energy photon field is :

$$\dot{D}_{x,y} = k \cdot TPR(d, r_d) \cdot S_h(x, y) \cdot S_p(r_d) \cdot ISL \cdot WF \cdot TF \quad (2.2)$$

where:

k is the dose per monitor unit at the calibration depth for the reference field size (usually $10 \times 10 \text{ cm}^2$). $TPR(d, r_d)$ is tissue phantom ratio at depth d for a field whose equivalent square side at this depth is r_d . $S_h(x, y)$ is the head scatter factor for the field size defined by the collimator settings x and y . $S_p(r_d)$ is the phantom scatter factor for a field whose equivalent square side at depth d is r_d . ISL is the inverse square law correction applied whenever the distance from the radiation source is different than the reference condition.

WF and TF are the wedge factor and the tray factor respectively and are applied to correct for beam attenuation when these accessories are present.

As mentioned above it is necessary to separate $S_{h,p}$ into head scatter and phantom scatter since they can vary independently when the field size at the phantom surface differs from the collimator setting (i.e. blocked field, extended treatment distance). For example, if shields are used to block a portion of the incident photon beam, the phantom scatter reaching the calculation point will be reduced due to the decreased irradiated volume of the phantom, while the head scatter under most situations (depending on the distance of the shields from the source and the extent of shielding) will change by less than 1%^{8,10}.

In routine dose calculations, TPR and S_p values are determined from tables which list only square field values. For rectangular fields the side of the equivalent square r_d can be determined from published tables which are based fundamentally on the Clarkson sector integration method²⁴ or can be calculated from the Sterling²⁵ equation

$$r_d = \frac{4A}{P} \quad (2.3)$$

where A and P are the area and perimeter of the rectangle respectively.

Due to the collimator-exchange effect which is investigated in this work and by other authors^{9,26}, S_h values are tabulated for rectangular fields. The collimator-exchange effect arises from the fact that the two pairs (Upper and Lower) of collimators defining the field

dimensions are at different distances from the source. As such, the amount of scatter reaching the phantom from the head components above the collimator jaws will depend on which jaw pair defines the width (x) and which defines the length (y) of the rectangle. Thus $S_h(x,y) \neq S_h(y,x)$ and hence neither the equivalent square table nor eqn. 2.3 can be utilized. Recently Vadash et al²⁷ have proposed an expression, with a single machine dependent variable, for determining the side of the equivalent square which has the same S_h value as a rectangular field.

2.3 Influence of Asymmetric Collimation on Dosimetric Parameters

The effects of asymmetric collimation on dose distribution, beam profile and beam quality have been reported in the literature^{10,28,29,30}. When a field is asymmetrically collimated, one needs to consider how changes in head scatter, phantom scatter, and off axis beam quality affect the dose to a point in the phantom.

The variation in off-axis beam quality was first reported by Hanson et al¹⁵ and its influence on the primary dose component was later investigated by Kepka et al¹⁶. The latter workers reported a dose error of up to 10 % at the periphery of a large field if the change in the spectral quality of the primary photon fluence with off-axis distance is not considered during dose calculations. These spectral changes arise principally as a consequence of the beam flattening filter which causes greater beam hardening near the central axis than at the beam periphery.

In order to account for the effects of asymmetric collimation on dose distribution, a number of different techniques have been proposed to calculate dose to points off-axis^{5,10,30,31,32,33}.

Some workers^{10,33} have suggested that off-axis dose calculations should be performed using central axis data, i.e. use symmetric field data (TPR , S_p , S_r , etc) measured on the central axis, and then multiply the calculated value by an off-axis ratio (OAR). This ratio is dependent on off-axis distance, depth in the phantom and side of the equivalent square field. The simplest recommendation^{10,33} was to equate the OAR to the off-axis ratio obtained from the largest symmetric field profile. However, it has been pointed out that although the profile data does include off-axis variations in beam quality and fluence, it also contains field size dependent changes in the relative scatter contribution within the phantom³⁴. It has also been reported that the measured profiles for the largest symmetric field drops off rapidly due to a reduction in scatter in the vicinity of the field edge and if no correction is applied, an average error of 3 % may be introduced in the OAR values for large beam offsets and small fields. Consequently the OAR values obtained from a single beam profile are not sufficient for accurate asymmetric field dose calculations^{35,36}. Chi and Mohan³⁰ have modified this approach by separating OAR into the product of a primary off-axis ratio, ($POAR$), with a boundary factor describing the shape of the beam edge at the point of calculation. Other workers^{34,35,37} have extended this technique to improve the determination of the $POAR$ component of dose at the off-axis point.

Kwa et al⁵ have proposed modifying large field profile data with an empirically determined correction factor based on Day's equivalent field calculation. Recently Gibbon et al³⁶ have proposed a new method for the calculation of *OAR* based on an extended form of Day's technique, in which the effects of changes in off-axis beam quality and intensity are incorporated.

The basic assumption in each of these off-axis dose calculation methods is that the head scatter for an asymmetric field is equal to that of a symmetric field of the same equivalent square. This implies that the head scatter factor is independent of off-axis distance for fields with the same area to perimeter ratio (A/P). In the present work I test the validity of this assumption and have found it to be in error by up to 1.7% in the S_h values for small asymmetric field sizes at large off-axis distances. Additionally, the use of the equivalent square in the calculation of S_h ignores the collimator-exchange effects which will introduce an additional error of up to 3%^{9,26,27}.

2.4 Measurement of S_h

It is commonly understood that in order to properly measure S_h , the ionization chamber and its buildup material should satisfy the following requirements^{9,26,27}

1. The thickness (g/cm^2) of the buildup material covering the ionization chamber must be sufficient to absorb the contaminant secondary electrons in the incident photon beam.

2. The buildup material covering the ionization chamber must be thick enough (g/cm^2) to achieve both longitudinal and lateral electron equilibrium (**LEE**).
3. The ionization chamber and its surrounding material should be sufficiently small to be encompassed by the photon beam and provide minimum phantom scatter.

There are two known techniques for measuring S_h which satisfy the above guidelines.

These are:

1. Using an ionization chamber with a buildup cap. Buildup caps have been made of polystyrene⁹, acrylic^{15,40}, brass⁹, lead⁴⁰, graphite⁶, aluminum⁴¹ and PTFE⁴² to obtain S_h data. When low density material is used the dimensions of the buildup cap for high energy photon beams will become too large for small field size measurements. To overcome this problem, buildup caps made of high Z material have been used. For low energy megavoltage beams, it has been reported⁴³ that high Z buildup caps produce a significant difference in S_h values from those measured with acrylic. However no such difference was observed when a Pb cap was used in a 6 MV or higher energies⁴⁰.
2. The use of a beam coaxial narrow cylindrical miniphantom^{26,39} made of water equivalent material. In this technique the ion chamber can be at depths greater than those used with a conventional buildup cap while still satisfying condition 3 above. The larger measurement depth provides several advantages³⁹ including: congruence with dosimetry protocols, the removal of electron contamination effects and the

elimination of errors due to the shift in the depth of maximum dose as a function of field size.

Several groups have used these techniques to measure S_h values. Van Gasteren et al³⁹ used a 4 cm diameter polystyrene miniphantom to measure S_h for beams ranging from ^{60}Co to 25 MV beams. Other workers have employed a 4x4 cm² cross section acrylic miniphantom for 6 and 25 MV photon beams^{26,27}. Zhu and Bjrnrgard⁴⁰ have reported using a Pb buildup cap with top and side wall thickness of 3.5 g/cm² for a 6 MV beam and achieving similar results to those obtained using a 4x4 cm² cross section acrylic miniphantom. Recently Frye et al⁴¹ have reported good agreement (within 0.5%) between data measured using a 4 cm diameter solid water miniphantom and a graphite buildup cap for 4 and 6 MV beams. They have also demonstrated, using strong magnetic fields, that contaminating electrons can have a significant effect on S_h values for high energy photon beams.

In the present work the effects of lateral electron equilibrium (**LEE**) and electron contamination on head scatter factor measurements obtained using water equivalent miniphantoms and high Z caps have been investigated. The minimum beam radius required to achieve full **LEE** in-water has been calculated by EGS4 Monte Carlo simulations. Particular attention has been focused on the effect of lateral electron disequilibrium and electron contamination conditions on the determination of S_h . We also

report on a comparison of results obtained in a polystyrene miniphantom to those from brass build up cap measurements.

2.5 Scatter Contributors and their Magnitude

The change in S_h as a function of symmetric field size can be attributed to a concomitant change in forward head scatter arising from the modified collimator opening. It can also be attributed to field size dependent collimator backscatter into the beam monitor chamber. The next two sections consider the effects of these two different types of scatter on linac output as a function of field size. The relative contribution of the various head components to the forward scatter are also examined for different linacs.

2.5.1 Backscatter to Monitor Chamber

Backscattered electrons and low energy photons are produced when the incident photon beam interacts with the top surface of the secondary collimators facing the beam monitor. For small field sizes a larger cross section of the collimator jaws is exposed to the beam resulting in greater backscatter and hence more charge collected by the beam monitor chamber. As a result, the beam monitor chamber will collect more charge for the same forward photon fluence and consequently the linac feedback control circuitry will reduce the electron beam current and the machine output (cGy/mu) will be reduced. Conversely, as the collimator jaws are opened, the backscatter radiation is reduced as a result of the smaller irradiated area of the collimator top surface and the linac output will increase.

The backscatter phenomenon is inversely dependent on the distance from the collimator jaws to the monitor chamber. It is also a function of the chamber wall density and thickness. Linacs supplied by the various vendors have diverse treatment head geometries and chamber designs and hence the extent of the backscatter influence on S_h varies dramatically among linac types. Different researchers have reported several methods of measuring backscatter radiation (BSR).

Patterson and Shragge⁴⁴ reported a 10% BSR contribution to the field size dependent output of an AECL Therac-20 18 MV photon beam. Their work consisted of indirectly determining the target beam current as a function of field size by measuring the forward-emitted photon fluence rate by photoactivation of copper foils placed very close to the target.

By maintaining a fixed field size at the phantom surface with the aid of two lead alloy blocks situated a distance apart, each with a 6.3mm diameter hole, Kubo¹¹ performed output measurements in-air with variable collimator opening. He reported a 7.5% field size dependence on BSR for the AECL Therac 20, but less than 2% for both the 6 and the 18 MV x-ray beams from a Varian 1800. Luxton and Astrafer⁴³ assessed the effects of backscatter to the beam monitor by covering the downstream portion of the monitor with 2.4 and 5.7 mm thick acrylic sheets. They estimated the thinner acrylic sheet absorbed 75 % of backscatter radiation and reported that a maximum of 8.4% of the monitor chamber response is due to BSR for a 23 MV photon beam produced by a CGR Saturne

25. Watts and Ibbot¹² were able to measure the current produced in the bremsstrahlung target by the incident electron beam and concluded negligible BSR contributions for a 10 MV beam from a Clinac 18. Duzenli et al⁷ used Kubo's experimental arrangement to show a maximum of 2.5% and 4 % BSR effects on the output for 6 and 18 MV beams respectively from a Varian Clinac 2100c linac. Negligible BSR contribution was observed for a 6 MV beam from Clinac 600c. They attributed this difference to dissimilar monitor chamber construction for the two accelerators.

Huang et al¹³ operated four Siemens linacs with photon energies ranging from 6 to 15 MV and a Varian Clinic 4 with a 4 MV beam without dose rate feedback control (i.e., with constant electron beam current in the linac). In all cases they reported negligible BSR effects on machine output.

In this work the contributions to beam monitor chamber from collimator backscatter radiation has been investigated for a Siemens KD2 linac. Two procedures were used to determine the extent of BSR contribution as a function of field size. In the first, the linac was operated without dose rate feedback control and the second method consisted of measuring the charge produced in the bremsstrahlung target by the incident electron beam. This is described in detail in chapter 3.

2.5.2 Forward Scatter from the Treatment Head

Head scatter includes all photons incident on the phantom which have undergone interaction with the treatment head components, including the electron beam stopper, primary collimator, flattening filter, beam monitor chamber, mirror and collimator jaws. From their experimental work, Kase and Svensson⁹ concluded that head scatter is dominated by the flattening filter and is relatively independent of energy and machine. From measurements performed on a 23MV beam (CGR Saturn 25), Luxton and Astrahan¹³ have shown that the scatter from the flattening filter and secondary collimators as well as the backscatter into the monitor chamber are field size dependent and have a maximum contribution of 10%, 8.6% and 8.4% to the output respectively. Mohan et al⁴⁵ performed Monte Carlo simulations and found that for a 15 MV photon beam from a Clinac 20, 93.5% of the photons arriving at a scoring plane 100 cm from the source suffered no collision, while 2.8% scattered from the primary collimator, 3.5% scattered from the flattening filter and 0.2% scattered from the secondary collimators. The field size was not specified. Based on a model in which the scatter from the flattening filter and primary collimator was assumed to originate from a distributed source at the level of the flattening filter, Dunscombe and Nieminen⁶ arrived at a ratio of 11.5 for primary (unscattered) to scattered radiation for a 20 x 20 cm² field from a Siemens KD2 6 MV beam. In an independent study using Monte Carlo simulations, Chaney et al²¹ determined a ratio of 10.4 for a 28.6 x 28.6 cm² from a similar linac. They also reported that the

scatter from the primary collimator, flattening filter and the electron beam stopper accounted for 3.7%, 2.5%, and 1.7% respectively of the total photons scored at isocenter. By extrapolating the magnitude of the primary fluence from head scatter factor measurements for small field sizes, Zhu et al⁴⁰ have estimated the magnitude of scatter photons from the various head components. The head scatter in the absence of the flattening filter contributed 5% to the central axis fluence in a 40 x40 cm² for a 6 MV beam from a Philips SL75-5. They also observed that the fluence increased with field size by up to 11% due to photons scattered in the flattening filter.

Chapter 3

Material and Methods

3.1 Introduction

The present work is comprised of both experimental techniques and Monte Carlo simulations. This chapter describes the experimental procedures and discusses the use of the Monte Carlo code including:

1. Experimental examination of the effects of lateral electronic equilibrium (**LEE**) and electron contamination when the head scatter factor is measured using a miniphantom or brass buildup cap. This work also employs Monte Carlo calculations to examine the minimum beam radius required to achieve full **LEE** in-water.
2. Empirical determination of the magnitude of backscatter radiation into the linac monitor chamber.
3. Experimental investigation of the behavior of S_h as a function of field size, field shape, photon energy and off-axis distance.
4. Measurement of the collimator-exchange-effect.
5. Measurement of the influence of the flattening filter on S_h .
6. Monte Carlo simulations of the relative contributions of the individual and combinations of head components to the primary and total photon fluence spectra at both on-axis and off-axis positions.

7. Monte Carlo simulations of the scatter fluence and its fluence weighted mean energy for a photon beam with individual and combinations of head components.
8. Monte Carlo modeling of the polystyrene miniphantom for comparison with measured S_h data and for the determination of the primary-to-scatter fluence and energy fluence ratios for use in the S_h estimation model.

3.2 Overview of Monte Carlo Simulations

Monte Carlo methods simulate the interaction of photons and electrons with matter by using the probability distributions which govern the physical processes by which the individual interactions occur⁴⁶. Random numbers, generated by computer, are used to sample from the known probability distributions. Using this process, large numbers of histories (events) are followed in order to obtain information on the average quantities and their distributions such as the energy deposited and the energy fluence.

In this work the EGS4 (Electron-Gamma-Shower version 4) Monte Carlo system of computer codes⁴⁷ has been used. It is a general purpose package for the simulation of the coupled transport of electrons and photons in any material for particles with energies above a few KeV up to several TeV. The following physical processes are incorporated into this code⁴⁷:

1. Bremsstrahlung production which is the production of a photon due to the sudden deceleration of the electron in an inelastic interaction with the Coulomb field of the nucleus .

2. Positron annihilation in flight and at rest.
3. Moliere multiple scattering which accounts for elastic scattering of electrons by the Coulomb field of the nucleus.
4. Moller and Bhabha cross sections which account for the inelastic scattering of the electron and positron respectively by the atomic electrons and resulting in delta ray formation.
5. Photon interaction processes including pair production, Compton scattering, coherent (Rayleigh) scattering and the photoelectric effect.

The cross section and branching ratio data for any element, compound or mixture defined by the user are generated by a program known as PEGS4. This is a preprocessing code whose output is used as input to the EGS4 Code.

In this work the Monte Carlo simulations were calculated by either the DOSRZ⁴⁸ or the ACCEL⁴⁹ EGS4 user codes. Both of these codes simulate the passage of an electron or photon in a finite, right cylindrical geometry. The absorbed dose (calculated by DOSRZ) and particle fluence or energy fluence (calculated by ACCEL) are the scoring quantities calculated in this work.

The geometry of the structure in which the interactions are to be modeled must be described. This is established by the input of a number of planar and cylindrical coordinates (object) which divide the cylinder into regions and whose material composition is defined by the user. Figure 3.1 illustrates the manner by which the

treatment head components are simulated by cylindrical /plane sections (see section 3.6 for more detail).

There are several parameters used by EGS4 which the user must provide and which have a significant effect on the accuracy of the scoring quantities. These critical parameters are referred to as: AE, AP, ECUT and PCUT. AE and AP are the energy thresholds for “catastrophic” interactions⁴⁶ of electrons or positrons, which will produce energetic secondary electrons (delta-rays) or photons respectively. These events will cause the primary particle to lose energy and be deflected. The secondary particle thus created, will have a separate path which must also be tracked and modeled in EGS4 Monte Carlo simulations. Any electron interaction which produces delta-rays with a total energy $\geq$ AE, or a bremsstrahlung photon with an energy $\geq$ AP, is considered to be discrete event⁴⁷. All other interactions are considered continuous and give rise to continuous energy losses and to directional changes to the electron between discrete interactions. The energy losses are due to soft interactions with the atomic electrons (excitation and ionization loss) and to the emission of soft bremsstrahlung photons. The changes in direction are mostly due to multiple Coulomb scattering from the nucleus, with some contribution coming from soft electron scattering. The choice of the energy thresholds for determining the creation of secondary electrons or photons as discrete events is arbitrary and a component of the algorithm, not of the physical process

Figure 3.1 Monte Carlo Modeling of Head Components

Modeling the treatment head components for input into EGS4 Monte Carlo codes. Samples of the cylinders and planes are shown as vertical and horizontal dashed lines respectively.

involved⁴⁶. ECUT and PCUT are the energy cutoff below which the electron (positron) and photon history are terminated respectively. Upon termination, the remaining energy of the particle is deposited locally.

In the EGS4 simulations performed during our investigations, the PRESTA⁵⁰ electron transport algorithm was invoked. PRESTA provides several features including:

1. A path-length correction algorithm which considers the differences between the straight path length and the total curved path length for each electron step.
2. A lateral correlation algorithm which takes into account lateral transport.
3. A boundary crossing algorithm which ensures that electrons are transported accurately in the vicinity of interfaces.

3.3 S_h Measurements - Material and Overview of Methods

By definition, the change in S_h with field size must be a function of head scatter alone. In order to accurately determine S_h , the effect of S_p (phantom scatter) must be removed from the measurement. This can be achieved by fixing the detector-radiation source geometry and by making S_p both small and constant as a function of field size.

In this work this is realized through phantom design. The requirement of the phantom is that it satisfies the need for buildup and provides **LEE**.

Two types of phantom were designed and used in this study. These are the cylindrical polystyrene “miniphantom” and the brass buildup cap, both shown in figure 3.2.

For all studies, the phantom thickness between the ion chamber and the radiation source was fixed at 5 g/cm^2 . For the LEE experiments the miniphantom diameter and brass cap side-wall thickness was varied.

The ion chamber used for all S_h measurements was a Scandronix⁵¹ cylindrical ion chamber, model RK, serial # 2100. This chamber has a volume of 0.12 cm^3 and an active length of 1 cm.

When used with the polystyrene miniphantom the RK chamber was oriented with its long axis perpendicular to the beam central axis. Conversely, when used with the brass buildup cap, the RK chamber was oriented with its long axis parallel to the beam central axis. The center of the active volume of the ion chamber was considered to be the point of measurement which was maintained at 80 and 100 cm from the source for ^{60}Co and linac measurements respectively.

The RK ion chamber was connected to a Nuclear Enterprise⁵² (N.E) electrometer, model 2570/1, serial # 1138. The electrometer was set to 0.6 cm^3 chamber mode and the range was set to high. Unless otherwise specified measurements were all made by integrating the charge collected by the RK chamber for an exposure corresponding to 100 monitor units (m.u) or 1 min. for ^{60}Co unit exposure. All measurements were repeated twice and the arithmetic average is reported in the results. Data were collected for many symmetric and asymmetric fields and these are listed in tables 3.1, 3.2a) and 3.2b). To assess the experimental precision (reproducibility), the output of a control field size

($10 \times 10 \text{ cm}^2$) at the central axis was recorded every 6th measurement. The room temperature and pressure were recorded every hour during measurements.

Measurements of photon beams from 4 different therapy units; 3 linacs and 1 ^{60}Co unit, were made. The linacs included: two Siemen's KD2⁵³ (serial #s 1784 and 3333) providing 6 and 18 MV beams and a Siemen MDX (serial # 2071) producing 6 MV photons. The ^{60}Co unit was an AECL Theratron 780C⁵⁴ (serial # 271).

3.4 LEE and Electron Contamination Measurements and Simulations

As a result of the requirement to minimize the size of the phantom during S_h measurements, lack of LEE and electron contamination can introduce experimental errors. In this work Monte Carlo simulations and experiments were used to study this problem. In the Monte Carlo calculations the diameter of a photon beam incident on a semi-infinite water phantom was increased until LEE was obtained. Experimentally, the field size was fixed and the phantom size was changed in order to evaluate the effects of electron contamination and LEE on S_h data.

3.4.1 Monte Carlo Methods

LEE was determined by studying the ratio of the total dose to the total Kerma (the energy transferred by photons to electrons per unit mass) as a function of photon beam radius incident on a 30 cm thick water phantom. As the beam radius is increased this ratio will increase until it reaches unity. At this point lateral electronic equilibrium is

assumed to have been achieved¹⁸. This should then represent the appropriate phantom diameter required to achieve **LEE**.

The DOSRZ Monte Carlo user code was used to calculate the central axis depth dose and the Kerma for photon beams incident directly on the water phantom. The terms dose and Kerma are used in this study to indicate total dose (primary + scatter) and the total Kerma, (collision + radiative) respectively. In order to score total Kerma the energy transferred from the photon to the electron is not allowed to be transported from the interaction site and is forced to be absorbed locally in the material. This is achieved by choosing ECUT (the energy cutoff below which the electron is terminated) to be equal to the maximum incident photon energy. For dose scoring ECUT was made equal to 0.521 MeV (Total energy which includes the electron rest mass of 0.511 MeV) which implies that the electron is allowed to be transported until its kinetic energy reaches 0.01 MeV before it is terminated with the remaining energy deposited locally. AE (the lowest energy for the creation of secondary electrons) was set equal to 0.511 MeV (total energy which includes the electron rest mass). PCUT and AP, the photon equivalents of ECUT and AE, respectively, were set to 0.01 MeV.

The code was run on a VAXstation 4060. The cross section data for the material used in the simulation (air and water) were generated by PEGS4 and used as an input to DOSRZ. The calculations were made for a point source 80 and 100 cm from the phantom surface to represent a ⁶⁰Co and a linac x-ray beam respectively. The space between the source and the phantom was filled with air for the simulations. The dose and Kerma were

scored in a 0.2 cm thick disc shaped region whose radius was defined at the phantom surface.

For incident beam radii greater than 0.5 cm, the scoring region radius was 0.5 cm. For beam radii < 0.5 cm the scoring region radius was set the same as the incident beam radius. The ^{60}Co incident beam spectrum included a 30% photon fluence contribution from the source capsule and collimator scatter⁵⁵. For the LEE calculations, the input x-ray beam spectra were from Mohan et al⁴⁵. The Monte Carlo calculations were made for a sufficient number of histories to reduce the statistical uncertainty (the standard deviation) of the total dose in each individual depth bin to few tenths of a percent.

3.4.2 Influence of Electron Contamination and LEE on the Measurement of S_h .

LEE and electron contamination are important factors which, when ignored, can introduce errors into the determination of S_h . It is important that the buildup caps or miniphantoms used to obtain S_h data be as small as possible such that phantom scatter does not have an influence on the value of S_h . However, as conventional buildup caps are made small enough not to be considered as phantoms, electron contamination and lack of electronic equilibrium begin to plague the measurement. This work examines the effect of phantom size and composition on the measurement of S_h .

Two phantom types are considered, polystyrene (density = 1.04 g/cm³) cylindrical miniphantom and brass (density = 8.56 g/cm³) buildup caps. The design of these

phantoms is illustrated in figure 3.2. The miniphantoms, constructed as described by van Gasteren et al³⁹, were manufactured with diameters of 1.0, 1.5, 2.0, 3.0, and 4.0 g/cm².

Brass buildup caps were also used in this work since their high atomic number should provide electronic equilibrium and eliminate electron contamination while still preserving a small enough dimension. Brass caps with side-wall thickness of 0.1, 0.5, 1.0, 2.0, 3.0, and 3.5 g/cm² have been used in this study.

S_h measurements with the miniphantoms or brass caps were made on the central axis and the setup was as described in section 3.3. Data were collected for 6 and 18 MV photon beams produced by the Siemens KD2 linac (serial # 1784) and ⁶⁰Co. The set of the square fields used in the experiment is listed in table 3.1.

3.5 Measurement of Backscatter into the Monitor Chamber

This thesis addresses the change in linac output, principally S_h , as a function of field size. The output of a clinical linac is controlled via a feedback loop from an ion chamber or monitor chamber placed in the head of the therapy unit. The measurements described in this section are intended to determine how much of the field size dependent change in machine output is caused by electron or photon backscatter from the anterior surface of the collimator back into the monitor chamber. These effects are difficult to separate from other head scatter effects using the conventional methods of output and S_h measurement. Two different methods for this measurement were used and are described below.

Figure 3.2 Phantom Design for S_n Measurements

The phantom utilized in S_n measurements. The long axis of the RK chamber was parallel to the beam central axis when the brass cap was used to provide buildup and perpendicular to it when the polystyrene miniphantom was used.

Table 3.1 Dimensions of Symmetric Fields Used for the Central Axis S_z measurements

Square Fields (cm ²)	Rectangular Fields (cm ²) (XxY)			
4x4	4x5	5x4	8x5	5x8
5x5	4x6	6x4	8x6	6x8
6x6	4x7	7x4	8x7	7x8
8x8	4x8	8x4	8x8	8x8
10x10	4x10	10x4	8x10	10x8
12x12	4x12	12x4	8x12	12x8
15x15	4x15	15x4	8x15	15x8
20x20	4x20	20x4	8x20	20x8
25x25	4x25	25x4	8x25	25x8
30x30	4x30	30x4	8x30	30x8
35x35	4x35	35x4	8x35	35x8
40x40	4x40	40x4	8x40	40x8
	5x10	10x5	5x20	20x5

Table 3.2a Dimensions of Asymmetric Fields Used in the S_u Measurements

OFF-Axis Distance (cm)						
2	4	5	6	8	10	12
$X \times Y^*$ (cm ²)	$X \times Y^*$ (cm ²)	$X \times Y$ (cm ²)	$X \times Y^*$ (cm ²)	$X \times Y^*$ (cm ²)	$X \times Y^*$ (cm ²)	$X \times Y^*$ (cm ²)
4x4	4x4	4x4	4x4	4x4	4x4	4x4
5x5	5x5	5x5	5x5	5x5	5x5	5x5
6x6	6x6	6x6	6x6	6x6	6x6	6x6
8x8	8x8	8x8	8x8	8x8	8x8	8x8
10x10	10x10	10x10	10x10	10x10	10x10	10x10
12x12	12x12	12x12	12x12	12x12	12x12	12x12
15x15	15x15	15x15	15x15	15x15	15x15	15x15
20x20	20x20	20x20	20x20	20x20	20x20	
25x25	25x25	25x25	25x25		4x10	
30x30	30x30	30x30			4x20	
35x35					4x30	
					20x4	
					30x4	
					6x20	
					6x30	
					30x6	

* Y is the asymmetric side and was defined by the upper jaws (U)

Table 3.2b Dimensions of Asymmetric Fields Used in the S_v Measurements

OFF-Axis Distance (cm)					
2	4	5	6	8	10
$X' \times Y$ (cm ²)	$X' \times Y$ (cm ²)	$X' \times Y$ (cm ²)	$X' \times Y$ (cm ²)	$X' \times Y$ (cm ²)	$X' \times Y$ (cm ²)
4x4	4x4				
5x5	5x5				
6x6	6x6	6x6			
8x8	8x8	8x8	8x8		
10x10	10x10	10x10	10x10		
12x12	12x12	12x12	12x12		
15x15	15x15	15x15	15x15	15x15	
20x20	20x20	20x20	20x20	20x20	20x20
25x25	25x25	25x25	25x25		
30x30	30x30	30x30			

* X is the asymmetric side and was defined by the lower jaws (L)

Measurements were made for both the 6 and 18 MV beam from the Siemens KD2 (serial # 1784).

3.5.1 Disabling Feedback Control

The feedback from the monitor chamber to the beam current and pulse frequency controls were disabled. The linac field size was varied from 4x4 to 40x40 cm² in steps as listed in table 3.1. The total charge collected for a fixed time interval of 30 seconds was recorded for each field size. The integration time was set by the electrometer and the linac beam was stabilized prior to integration and turned off after the completion of charge collection.

The feedback control from the monitor chamber was then enabled and the above experiments repeated. The differences in the total charge collected between the two sets of measurements, for a particular field size, should reflect the backscatter effects into the monitor chamber.

3.5.2 Direct Measurement of Target Electron Current

The second method of measuring the influence of field size dependent backscatter into the monitor chamber required the measurement of the electron beam current incident upon the bremsstrahlung target. The change in the ratio of the total # of monitor units to total beam current is a function of backscatter into the monitor chamber. The total beam current incident onto the bremsstrahlung target is reflected by the total charge deposited

into the target. Thus the amount of charge that will be collected from the target is proportional to the beam current and this in turn is proportional to the amount of bremsstrahlung produced in the target.

In this work the total charge was determined by employing the circuit of figure 3.3. The total charge deposited in the target will charge the capacitor C1. At the end of each 100 m.u. exposure the voltage across C1 was determined using a sample and hold circuit. The capacitor was then discharged and set ready for the next exposure. The linac field size was varied from 4x4 to 40x40 cm² in steps as listed in table 3.1.

3.6 Determination of Factors Influencing Head Scatter

The various factors which influence the behavior of head scatter were determined experimentally and by using Monte Carlo simulations. The effects of field size, field shape, photon energy, off-axis distance (OAD), collimator-exchange-effects and the flattening filter on head scatter factor (S_h) were investigated experimentally. However, to determine the magnitude of the contribution of other individual head components such as the electron beam stopper, the primary and the secondary collimators, the mirror and the monitor required Monte Carlo simulations. Essentially this is because it is not practical to remove these components on a clinical therapy unit for measurement purposes. Although the Monte Carlo code used in this work only allows symmetric field geometries, judicious use can reveal the relative importance of the individual head components in terms of their contributions to the total scatter to both on-and to off-axis

points of interest. In addition these results have assisted in the development and understanding of the model for asymmetric field head scatter factor estimations described in chapter 5.

3.6.1 Experimental Determination of the Effect of Energy on S_h

The influence of changing the linac effective photon energy on the determination of S_h was investigated. Two sets of data were collected, with and without the flattening filter. In the presence of the flattening filter, S_h measurements were made for both 6 and 18 MV photon beams produced by the Siemens KD2 (serial # 1784). Exposure measurements were made using the N.E electrometer with the RK chamber placed in a 3 g/cm² diameter polystyrene miniphantom with a setup as described in section 3.3.

S_h measurements were also made while the flattening filter was absent from the treatment head. Details of the experimental setup are in section 3.6.5.

3.6.2 Experimental Determination of Field Size and Shape Effects on S_h

S_h data as a function of field size were collected on the central axis for the square and rectangular fields listed in table 3.1. Furthermore S_h measurements were repeated for asymmetric square and rectangular fields defined at various off-axis distances as listed in table 3.2a. Measurements were made for both the 6 and 18 MV beam from the Siemens KD2 (serial # 1784).

Figure 3.3 Circuit Used to Measure Target Electron Current

3.6.3 Experimental Determination of the Variation in S_d as a function of Off-Axis Distance

Off-axis distance is defined as the distance from the field center to the collimator central axis. It is measured in a plane perpendicular to the central axis and on a line passing through the linac isocenter. At any particular off-axis distance one side of the square was asymmetric while the other side was maintained symmetric with respect to the central axis. One set of measurements was obtained with the upper jaws (U) defining the asymmetric side of the square at 2, 4, 5, 6, 8, 10 and 12 cm OAD. Another set was collected with the lower jaws (L) establishing the asymmetry. In this case the maximum OAD was 6 cm. The square field sizes used in the above measurements, at any particular OAD, are listed in table 3.2a and 3.2b for the upper and the lower jaw defined asymmetry respectively.

S_d measurements were also made for a set of asymmetric rectangular field sizes at 10 cm OAD. The asymmetry was defined by the upper jaws and the field sizes used are shown in table 3.2a.

Beam measurement was performed using the N.E. electrometer with the RK chamber placed in a 3 g/cm² diameter polystyrene miniphantom. The miniphantom axis was oriented parallel to the beam central axis for all measurements. At each OAD all readings were normalized to the value measured for a 10x10 cm² field.

3.6.4 Experimental Determination of Collimator-exchange Effects on S_h

To examine collimator-exchange effects, S_h data were collected along the central axis for symmetric rectangular fields. The field length was made to vary while the width was held constant. When the fixed width was defined with the upper jaws, the variable field length was collimated by the lower jaws. Conversely, when the fixed width was defined by the lower jaws then the variable length was maintained by the movement of the upper jaws. Details of the rectangular dimensions are listed in table 3.1.

In addition to the beams described in section 3.6.1, the above experiment was repeated for a 6 MV beam from the Siemens MDX (serial # 2071). The TPR_{10}^{20} for both linacs were within 0.4%, the only difference between the two accelerators being the power source. One linac was powered with a klystron while the other was powered with a magnetron. The experimental setup and method were as above.

The collimator-exchange effect was also studied for asymmetric rectangular fields defined at 10 cm OAD. The asymmetry was defined by the upper jaws and the field sizes used are listed in table 3.2a.

In all the above conditions S_h was measured as described in section 3.3. The N.E electrometer and the RK chamber placed in a 3 g/cm² diameter polystyrene were used. At 10 cm OAD the miniphantom axis was oriented so as to be maintained parallel to the central axis. All readings were normalized to the value of the 10x10 cm² field.

3.6.5 Experimental Determination of Flattening Filter Effects on S_h

The flattening filter is thought to be a major contributor to the field size dependence of S_h ^{6,9,22,45} as discussed in section 2.5.2. In this work, S_h was measured as described in section 3.3 for the Siemens (serial # 3333), 6 and 18 MV beams with and without the flattening filter in place. S_h was determined for each case on the central axis as well as at 5 and 10 cm OAD. The square fields for which S_h was obtained are listed in table 3.2a. For these measurements the RK chamber was placed inside the brass buildup cap with a 2.0 g/cm² side-wall thickness. The chamber was oriented such that its long axis was always parallel to the beam central axis as shown in figure 3.2.

3.6.6 Measurement of Off-Axis Ratios

The off-axis ratio (OAR) is defined as the ratio of the dose at any specific off-axis distance to the dose on the central axis. This quantity was measured in order to examine its dependence on field size and to validate the OAR derived from Monte Carlo calculations which are discussed in section 3.8.

The OAR for a 40x40 cm² field were determined from measured beam profiles in-air and water for 6 and 18 MV from the KD2 linac (serial # 1784). The in-air measurements were made with the RK chamber inserted into a 1.5 g/cm² radius polystyrene miniphantom at 5 g/cm² depth. The data were collected in 1 cm steps from the central axis out to 15 cm OAD and the ionization readings were normalized to the central axis measured value. The miniphantom was oriented such that its long axis was maintained

parallel to the beam central axis throughout the experiment. For the in-water beam profiles the RK chamber was placed in an acrylic insert which was situated in a water filled acrylic tank of 40x40x30 cm³ volume. The chamber long axis was perpendicular to the beam axis. Its center was at a depth of 5 cm in the water tank and at 100 cm from the radiation source. The water tank was moved in 1 cm steps such that the position of the ion chamber was moved from the central axis out to 15 cm OAD and readings were taken at each position. To ensure phantom scatter equilibrium was reached at the extended OAD, 15 cm of acrylic sheets were attached to the side of the water tank closest to the central axis.

Using these in-air and in-water setups, the output was measured at the center of asymmetric square fields with side dimensions of 4, 6, 8, 10, 15 and 20 cm. For each field size OARs were determined by normalizing the readings obtained at 2, 4, 6, 8, 10 and 12 cm OAD to the central axis reading.

3.7 Error Estimates in S_h Measurements

For each experiment, the total measurement error could be attributed to the following uncertainties:

1. instability in the detection instrument (chamber/electrometer).
2. linac output variation.
3. positional errors of the chamber/phantom at on and the off-axis locations.

4. positional inaccuracies of the collimator jaws defining the symmetric and asymmetric fields.

The uncertainties from #1 to #3 above are considered random in nature and follow a normal distribution. As for the jaw positional inaccuracies (#4 above) the uncertainty could be random or systematic.

Systematic errors may arise from an incorrect collimator jaw position calibration or misalignment between the optical and radiation fields (see below). An incorrect jaw position could result in an error in the radiation field dimension and its location. This effect becomes significant for small field sizes resulting in a larger uncertainty in their calculated factors. An inconsistent (nonreproducible) jaw positioning is considered a random error in this work.

To estimate the combined effect of the random errors of #1 to #4 above on the collected dosimetric data in each experiment, the output of a control field size (10x10 cm²) at the central axis was recorded every 6th measurement. This entails the movement of the miniphantom or water tank from a particular off-axis distance to the central axis position and back to an off-axis location and the changing of the jaw positions. The standard deviation (σ) of the control field readings, which was calculated for each experiment, is taken to represent the combined random errors which are due to the detection instrument instability, the linac output changes, the measuring device positional

changes and the jaws position inaccuracies for the control field. This σ is taken to indicate the uncertainty associated with the readings for an individual field.

Recall that S_h is the ratio of the readings of two fields and the standard deviation in S_h (σ_s) is taken as the sum in quadrature of the estimated error (i.e. σ) of the individual field readings.

The effect of a possible random error in collimator jaw positioning (#4 above) on the measured data, was also investigated for the smallest field ($4 \times 4 \text{ cm}^2$) centered along the central axis and at 12 cm OAD. This was done by allowing one of the jaws to vary by 0.2 cm from its ideal position and the field output was recorded. These types of measurements were made for the 6 MV and the 18 MV beams from the KD2 linac (serial # 1784).

In all experiments the linac optical system was used to verify the position and size of the fields. Ideally any optically defined field should match the radiation field at the center and edges (defined by the collimator jaws). Any misalignment could translate to a systematic positional error. To determine the magnitude of this effect the congruence of the light and radiation field centers and edges were tested with x-ray films (Kodak XV2) placed at 100 cm SAD. To produce maximum dose build-up the film was covered with 1.5 (6 MV beam) and 3.0 (18 MV beam) g/cm^2 thick polystyrene sheets. 4×4 and $10 \times 10 \text{ cm}^2$ fields centered on the central axis and 12 cm off-axis were used. The positions of the linac light field center and edges were marked on the film by using a pin prick. The

film was developed in a film processor (Kodak RP X-OMAT) and the film optical densities were measured by a scanning densitometer (Multidata Film Scanner model # 9720)⁵⁶. Density profiles along the field width and length central planes were scanned with a 1 mm diameter light aperture. By using a measured density to dose calibration curve, for the appropriate photon energy, the corresponding dose profiles were calculated. Data normalization was to the dose at the field center and for each profile the distance between the 50% dose points was taken to be the radiation field size. The differences between the optical and radiation field centers and edges were thus determined. These data were collected for the KD2 linac (serial # 1784).

The majority of off-axis S_n measurements were made with a polystyrene miniphantom whose axis was maintained parallel to the beam central axis. This implies that the miniphantom did not orient with the beam divergence for all off-axis measurements. This could result in a systematic error. To investigate the effect this has on the determination of S_n , measurements were made with the miniphantom tilted such that its axis is coincident with the asymmetric field central ray at 12 cm OAD. The S_n values thus obtained were compared with those measured with the miniphantom axis oriented parallel to the beam axis. These type of measurements were made for the 6 MV and the 18 MV beams from the KD2 linac (serial # 1784)

3.8 Monte Carlo Determination of Head Component Effects on Scatter

Monte Carlo simulations were performed to examine the scatter contribution from the individual head components of the Siemens KD2. These components include the target, the electron beam stopper, the flattening filter, the monitor chamber, the mirror, the primary collimator and the secondary collimators. To study the scatter contributions from these head components, the primary and total fluence spectra (differential in energy) were determined along the central axis and at several off-axis positions for a 6 MV beam using the Monte Carlo user code ACCEL. These quantities were used to calculate the scatter fluence and energy fluence in the scoring regions from each of the head components studied.

In addition, the primary-to-scatter ratio of fluence and energy fluence were also obtained from the Monte Carlo results for the various scoring regions on- and off-axis. This primary-to-scatter ratio is an important parameter required in the model (see chapter 5) developed to estimate S_h for asymmetric fields. The polystyrene miniphantom used in S_h measurements was also modeled in ACCEL and head scatter factors as a function of beam size were derived. The contributions of the miniphantom to the scatter were also estimated.

3.8.1 Head Components Input into the Code

Proprietary engineering drawings of the Siemens KD2 accelerator were used to define the composition and geometry of the treatment head components. These included the exit window of the accelerator structure, the target, the electron beam stopper, the flattening

filter, the monitor chamber, the mirror, the primary collimator, the secondary collimators and air. The atomic/material composition of each of the head components is listed in table 3.3. The geometry of the head design is illustrated in figure 3.4.

The ACCEL user code simulates the passage of electrons and photons in a finite, right cylindrical geometry with azimuthal symmetry. The geometric structures to be modeled must be represented in this code by a number of parallel planes, separated by appropriate distances, and by different radii cylinders (see figures 3.1). These planes and cylinders define the boundaries of physical regions.

In order to satisfy the code input requirements and to model the linac head accurately, a large number of planes and cylindrical radii must be used. As a consequence, a large number of geometrical regions are formed where the material of each region must be defined by the user.

In this work the linac head was modeled using 46 planes and 29 cylinders such that 1335 geometrical regions were defined. As illustrated in figures 3.1 and 3.5 the cylinders' radii are established from a common origin. In the region where the flattening filter was located twenty cylinders were used to define annular regions each of 0.1 cm width.

The requirement for cylindrical geometry makes the exact modeling of the linac head impossible. As such a few deviations from the engineering drawings were made and these are discussed below.

Table 3.3 Modeled Linac Head Components Composition and Densities

Component	Material	Density (g/cm³)
Window	Titanium	4.54
Target	Gold	19.3
Primary and Secondary Collimators	Tungsten	19.3
Electron beam stopper	Carbon	1.76
Flattening filter	Stainless steel	7.76
Monitor chamber	Ceramic	3.57
Mirror	Glass	2.2

Figure 3.4 Illustration of the Head Design for the Siemens KD2 linac

Figure 3.5 Monte Carlo Scoring Region Geometry

The scoring plane consists of an annular regions around the central axis. Radius 'r' is the annulus distance center from the central axis. Off-axis angle " ϕ " is the angle between the central axis and the line joining the x-ray source and passes through the annulus centre .

1. The flattening filter was modeled as a stack of discs each of finite thickness, stacked in order of descending disc radius (see figure 3.1). This arrangement causes discontinuities in a stair step fashion at the flattening filter surface which in reality has a smooth curvature as shown in figure 3.4. Small adjustments to some of the stack disc thicknesses were deemed necessary in order to match the Monte Carlo calculated off-axis ratios with those measured in-water at 1.5 cm depth to within 3 %.
2. The mirror of the projected light field was modeled as a finite thickness disc whose surface is perpendicular to the beam axis. In reality the mirror is at an angle of approximately 45 degrees to the beam central axis.
3. In order to preserve symmetry, the upper and lower jaws were assumed to be of identical geometry. In most of our photon fluence calculations the position of both sets of jaws was modeled to be at the bottom edge of the upper jaws. This approximation will result in an error in calculated jaw scatter reaching the scoring region. In an attempt to estimate the magnitude of such an error, the photon fluence spectra calculations were repeated for a subset of field sizes where the position of both sets of jaws was modeled to be at the distal position of the lower jaws. In the remainder of this work the Monte Carlo modeled upper and lower jaws will be referred to as the secondary collimators.

A 0.15 cm radius beam of electrons incident normal at the exit window was used in the simulations. X-rays produced in the exit window, the target, and the electron beam

stopper by the primary electron beam and by the secondary charged particles as well as scattered x-rays were scored in-air at a plane perpendicular to the central axis at 100 cm distance from the target.

The scoring plane was divided into annular regions around the central axis as shown in figure 3.4. The radius ' r ' shown in the figure corresponds to the distance from the center of the annulus to the central axis. In polar coordinates this distance is determined by the angle ϕ between the central axis and the line from the x-ray source passing through the annulus center as shown in figure 3.4. This angle is referred to as the *off-axis angle*. Throughout this work the term scoring region(s) is used to represent these annular scoring region(s). In the plane of the linac isocenter (100 cm SAD) 10 scoring regions, each of 2 cm width were used.

Other than for the study of LEE work where Mohan's spectra was used, the photon spectra used for the modeled Siemens linac head were generated in this work. Simulations were made for incident electron beams of 6, 7 and 7.5 MeV. In order to determine which of these electron beams produced the photon spectra most closely matching the actual spectra, depth dose curves for a field radius of 5.6 cm (equivalent to a square of 10 cm side) were calculated using DOSRZ user code and compared to measured data. The input photon spectra utilized by DOSRZ were calculated by ACCEL user code for a 2 cm radius disc at the isocenter in-air and all of the linac head components, with the exception of the secondary collimators, were present in the

simulation. It was determined (see chapter 4) that the best approximation to the physical beam was given by a 7 MeV incident electron beam. Consequently this energy was used in the subsequent Monte Carlo simulations.

To verify that the head components are properly modeled, the off-axis ratios in-water, at 100 cm SSD (Source to skin distance) and 1.5 cm depth were derived using the ACCEL code as explained in the next section. These were compared to corresponding data obtained from a measured 40x40 cm² open beam profile. The OARs were found to exhibit a significant dependence on the flattening filter design.

The Monte Carlo simulations were repeated with modified flattening filter dimensions until the derived OARs were within 3 % of those measured. The ACCEL and DOSRZ Monte Carlo user codes were run on a Digital Alpha Server 2100.

3.8.2 The Monte Carlo Derived Quantities

For each geometric region of interest the primary and total fluence spectra (differential in energy), the total fluence, Φ_T , the primary fluence, Φ_P , the primary fluence weighted mean energies, $\bar{E}_P$, and the total fluence weighted mean energies, $\bar{E}_T$ were scored by ACCEL code.

The photon fluence (# of photons /unit area) in ACCEL is calculated as the total photon path length per unit volume. This quantity has been shown to be equivalent to the average fluence in the volume⁵⁷.

The primary fluence corresponds to those photons which have never scattered during their flight from production site to the scoring region. The total fluence is the sum of the scatter and the primary photon fluences. Thus, at any particular scoring region the scatter photon fluence spectra can be obtained by subtracting the primary fluence from the total fluence which were calculated by the code.

The fluence weighted mean energy, $\bar{E}$, is defined as:

$$\bar{E} = \frac{\sum_i^n \phi_i \bar{E}_i}{\sum_i^n \phi_i} \quad (\text{MeV}) \quad (3.1)$$

where ϕ_i is either the primary photon fluence or total photon fluence in the i^{th} energy bin,

$\bar{E}_i$ is the corresponding bin average energy and n is the total number of energy bins.

The scatter fluence weighted mean energy, $\bar{E}_S$, was derived in this work as

$$\bar{E}_S = \frac{\bar{E}_T \Phi_T - \bar{E}_P \Phi_P}{\Phi_S} \quad (\text{MeV}) \quad (3.2)$$

where $\bar{E}_T \Phi_T$ and $\bar{E}_P \Phi_P$ are defined as the total and primary energy fluence respectively

for the scoring region of interest. Thus $\bar{E}_S \Phi_S$ will be the corresponding scatter energy fluence.

Monte Carlo derived off-axis ratios (OAR_{MC}) in-water are defined as the ratio of the dose, D_r , in the scoring region whose center is situated at a distance r from the central axis to the dose at the central axis D_0 .

$$OAR_{MC} = \frac{D_r}{D_0} \quad (3.3)$$

Under charge particle equilibrium, CPE , conditions at a point in a medium, the absorbed dose, D , is equal to the collisional kerma⁵⁸, k_c . Hence

$$D \stackrel{CPE}{=} k_c = \bar{E}_T \Phi_T \left(\frac{\mu_{en}}{\rho} \right)_{E_T} \quad (\text{Gy}) \quad (3.4)$$

where $\bar{E}_T$ and Φ_T are defined above and $\left(\frac{\mu_{en}}{\rho} \right)_{E_T}$ is the mass energy absorption

coefficient of the material for energy $\bar{E}_T$. Values of $\left(\frac{\mu_{en}}{\rho} \right)_{E_T}$ were obtained from Berger and Hubbell⁵⁹.

3.8.3 Monte Carlo Estimation of Individual Head Component Scatter

A major focus in this work is to investigate the linac head scatter. To determine such a quantity, the photons scattered from each head component and reaching any particular scoring region at the isocenter must be determined. For a particular scoring region the photon scatter from the individual head components was obtained by subtracting the two

different scatter fluences (or scatter fluence differential in energy) calculated in two separate Monte Carlo runs. In one, the head component of interest was present in the simulation while in the second it was removed. For example, to estimate the scatter from the primary collimator, both the total and primary photon fluence were calculated with only the target, exit window and air present in the linac head from which the scatter fluence was derived by subtracting the primary from the total fluence. Next, the primary collimator was added to the model and the photon fluence spectra calculations were repeated. The increase in the photon scatter fluence reaching the scoring region would represent the scatter arising from the primary collimator. This method was repeated for the electron beam stopper, the flattening filter, mirror and dose monitor chamber.

Note the presence of the flattening filter will cause some of the scattered photons produced in the primary collimator and the electron beam stopper to be absorbed resulting in reduction of their contributions to the scoring regions. To estimate these effects the scatter fluence was first obtained in the presence of air, the beam stopper, the primary collimator and the flattening filter in the treatment head. Then only the electron beam stopper was removed and the calculations were repeated. Next only the primary collimator was removed from the simulation and finally both the stopper and the primary collimator were removed while the flattening filter and air remained for the calculations. The ratios of primary-to-scatter fluences and the energy fluences derived from the Monte Carlo simulations were calculated as a function of field size. These data were compared

with the ratios determined in the model developed in this work to calculate head scatter factors for asymmetric fields.

3.8.4 Monte Carlo Estimate of Head Scatter Factors

The polystyrene miniphantom was modeled in ACCEL as a cylinder of 20 cm height and 3 cm radius. The scoring region was a disc of 1 cm radius and 1 cm thickness whose center was at 5 cm depth in the miniphantom. All head components were present in the model and simulations were performed for different radii photon beams defined at 100 cm from the target. The size of the beam was determined by the positions of the secondary collimators. Head scatter factors were defined as either the ratio of total fluence, Φ_T , or the energy fluence, $\bar{E}_T \Phi_T$, of any beam size to that beam whose size was equivalent to a 10 x 10 cm² field.

3.9 Uncertainty Analysis in Monte Carlo Studies

The Monte Carlo codes used in this work (ACCEL and DOSRZ) score the required quantities in 10 independent “batches”, each considering the same number of histories. From these 10 batches the population mean and the standard deviation (σ_{MC}) are estimated assuming a normally distributed population.

The primary and scatter fluence (Φ_p and Φ_s) of each scoring region are presented as a ratio of the corresponding total fluence Φ_T . The overall uncertainty for these

quantities, including $\bar{E}_S$, was calculated as the sum in quadrature of the standard deviations (σ_{MC^S}) associated with each variable used in determining them.

Chapter 4

Results

This chapter presents the results of the experimental and Monte Carlo investigations described in chapter 3.

4.1 Error Estimates in S_h Measurements

As mentioned in section 3.6.7, the total error associated with the measured dosimetric data used in the determination of S_h could be attributed to the following uncertainties:

1. instability in the detection instrument (chamber/electrometer)
2. linac output variation
3. positional changes of the chamber/phantom at both on- and the off-axis locations.
4. positional inaccuracies of the collimator jaws defining the symmetric and asymmetric fields.

The first 3 are considered random in nature while the errors due to # 4 could be either random or systematic. The combined effect of all the random errors (see section 3.7) was estimated for each experiment by measuring the output of a control field size ($10 \times 10 \text{ cm}^2$) on the central axis. This was done every 6th measurement during the collection of the on-axis and off-axis data. The standard deviation (σ) of these readings was calculated and are presented as a percentage of the mean reading in table 4.1. There were a total of 8 independent experiments performed at different times and the maximum

σ observed standard deviation in the data was 0.15%. The value of σ for each experiment was taken to represent the uncertainty, due to the random errors, for the individual field readings.

Recall that S_h is the ratio of the readings of two fields and the standard deviation in S_h (σ_s) was taken as the sum in quadrature of the estimated error (i.e. σ) of the individual field readings. The values of the calculated σ_s are listed in table 4.1 and the maximum observed was 0.21% of the mean reading.

It is important to note that the graphic presentation of the results shown in the remainder of this work do not include error bars, in order to keep the graphs clear. However when results are presented, the control field standard deviation, σ , of the experiment is reported.

The effects of the random uncertainty of collimator jaw positioning on the measured data were also estimated for the smallest field ($4 \times 4 \text{ cm}^2$) centered on the central axis and at 12 cm OAD. This was done by allowing one of the jaws to vary by 0.2 cm from its nominal position and the field output was recorded. These types of measurements were made for the 6 MV and the 18 MV beams from the KD2 linac (serial # 1784). The maximum change in the readings was less than 0.25% from the nominal condition for the on and off-axis points of measurements.

In all of the experiments the linac optical system was used to verify the position and size of the fields. Since the corresponding radiation field size and its position is of

importance in this work, the congruence of the light and radiation field centers and edges were examined with x-ray film. 4 x 4 and 10 x 10 cm² fields centered on the central axis and at 12 cm off-axis were used for these tests.

The film results indicate that the dimensions of the radiation fields studied were within ± 0.1 cm of the requested value. Also the coincidence of the light and the radiation field centers and edges were determined to be within ± 0.1 cm for all cases investigated at the on- and the off-axis positions. These type of errors would normally be presented as error bars parallel to the positional axis.

The majority of off-axis S_h measurements were made with a polystyrene miniphantom whose long axis was maintained parallel to the beam central axis. This implies that the miniphantom did not orient parallel to the beam divergence at the field center for all off-axis measurements. This could result in systematic errors. To investigate the effect this has on the determination of S_h , measurements were made with the miniphantom tilted such that its axis was coincident with the asymmetric field central ray at 12 cm OAD. These were compared with data obtained while the miniphantom axis was maintained parallel to the beam central axis. These measurements were made for the 6 MV and the 18 MV beams from the KD2 linac (serial # 1784). The difference in S_h values measured with the two different miniphantom orientations was negligible.

Table 4.1 Experiments and S_h Standard Deviations

Experiment #	Control Field Head Scatter Factor (S_h)	Standard Deviation (%) [*]	
		Experiment (σ)	Control Field Head Scatter Factor (σ_s)
1	1.0	0.15	0.21
2	1.0	0.1	0.14
3	1.0	0.11	0.16
4	1.0	0.1	0.14
5	1.0	0.15	0.21
6	1.0	0.1	0.14
7	1.0	0.05	0.07
8	1.0	0.06	0.07

^{*} The standard deviation quoted as % of the mean readings

4.2 Error Analysis In Monte Carlo Studies

The Monte Carlo codes used in this work (ACCEL and DOSRZ) score the required quantities in 10 independent “batches”, each considering the same number of histories. From these 10 batches the population mean and the standard deviation (σ_{MC}) are estimated assuming a normally distributed population.

In general error bars are not displayed in the spectrum figures. A sample of the total photon fluence spectra (differential in energy) is displayed in figure 4.20 a) with error bars representing σ_{MC} from the mean bin value. Figure 4.20 b) shows the corresponding primary fluence spectra which is presented as a ratio of the total fluence. The standard deviation in this case was determined as the sum in quadrature of the estimated σ_{MC} s of the primary and the total fluence for the appropriate energy bin. These uncertainties are typical of all the fluence spectra calculated in this work. In the remainder of this work, to make the figures easier to read, error bars were not shown unless they differ significantly from those of figure 4.20.

The standard deviations associated with the primary and scatter fluences and the primary and scatter fluence weighted mean energies for the scoring regions are shown as error bars in the appropriate figures. Where applicable, these standard deviations were determined as the sum in quadrature of the estimated σ_{MC} for the individual components used in obtaining the results (see section 3.8).

Three important points should be considered regarding the general behavior and presentation of σ_{MC} s and these are : (1) The magnitude of σ_{MC} is larger for the central scoring region and decreases with increasing off-axis distance. This is because the area of the scoring region (annulus) increases with off-axis distance resulting in more histories being recorded than the central region and thus reducing σ_{MC} . (2) Due to the small number of photons scored in the higher energy bins ($> \sim 5$ MeV), the magnitude of σ_{MC} s increases to more than 5 % of the mean value. (3) In some of the later figures, the error bars are not visible for some of the data points in the curves because the errors are small and the scale used in these diagrams is too large for the errors bars to be seen.

4.3 Results of the LEE and Electron Contamination Studies

In this section the effects of the lateral electron equilibrium (LEE) on the ratio of dose to kerma as obtained by Monte Carlo calculations are presented. This is followed by the results of measurements examining the effect of the miniphantom and brass cap dimensions on S_h determination.

4.3.1 Monte Carlo study of lateral electron equilibrium

In order to observe the effects of photon beam size on LEE, Monte Carlo calculations were performed for narrow photon beams ranging from 0.05 cm to 3 cm in radius. These were simulated for clinical photon beams of ^{60}Co , 6, 10, 15 and 24 MV (Mohan's spectra). Figure 4.1 graphs the calculated ratio of the total dose to the total kerma scored

at a depth of 5 cm in-water. The scoring plane was 100 cm and 80 cm SSD for the x-ray beams and ^{60}Co respectively. In this figure it can be seen that for each energy studied the dose to kerma ratio reaches a maximum value of approximately 1.01 ± 0.01 . The radius at which the ratio reaches saturation is energy dependent, and monotonically increases with energy.

4.3.2 Influence of Electron Contamination and LEE on the Experimental Determination of S_k

This study was designed to examine the effects of phantom dimension (miniphantom or brass cap) on the experimentally determined value of S_k . The measurements were performed in polystyrene miniphantoms with radii of 1.0, 1.5, 2.0, 3.0 and 4.0 cm for ^{60}Co , 6 and 18 MV photons. Similarly, brass caps of side wall thickness of 0.1, 0.5, 1.0, 2.0, 3.0, 3.5 g/cm² were also used. The control field standard deviation, σ , of this experiment was 0.15% of the mean readings.

Figures 4.2 a) and b) present the non-normalised ionisation readings, typical of those measured, for miniphantoms of 3 different radii as a function of field size for 6 MV and 18 MV respectively. It should be noted that the measured ionisation increases as a function of phantom diameter, and as expected also increases as a function of field size.

Figures 4.3 a) and b) and figure 4.4 display similar data, renormalised and presented as head scatter factors for 6 MV, 18 MV and ^{60}Co beams respectively. Each S_k curve is normalised to a 10 x 10 field. Measurements are presented for miniphantoms of different radii and for

brass build-up caps of varying wall thickness. These data illustrate the importance of phantom dimension on the empirical determination of S_h curves. As can be seen for all energies and dimensions measured, an increase in miniphantom radius (or build-up cap side wall) used for the measurement, results in a decrease in the reported field size dependence of S_h .

Figures 4.5 and 4.6 present the same data and show the change in experimentally determined S_h value as a function of miniphantom or build-up cap dimension respectively. Each figure presents data for a 6x6 and a 20x20 field size for the 6 MV and 18 MV beam. It can be seen in figure 4.5 that for irradiation with a 20x20 cm² field, S_h decreases and asymptotically approaches a constant as the side wall thickness of the brass cap increases. Conversely, for a 6x6 field the calculated value of S_h increases and asymptotically approaches a constant as the side wall thickness of the brass cap increases. It can be seen that when the side wall thickness of the brass cap is greater than approximately 0.7 g/cm², S_h becomes invariant with changes in wall dimension (see insert in figure 4.5) for both 6 and 18 MV photons. When the build-up cap is removed there is a significant difference in the S_h value which is calculated. Figure 4.6 displays similar data for 6 and 18 MV photon beams when measured in a polystyrene miniphantom. In the case of the polystyrene miniphantom the calculated value of S_h becomes independent of phantom radius when the miniphantom radius exceeds approximately 1.0 g/cm².

Figure 4.1 Dose to Kerma Ratio vs Beam Size

The ratios of total dose to total kerma vs radius of incident beam defined at 100 cm and 80 cm SSD for x-rays and ^{60}Co photon respectively. The calculations were made for a point on the central axis at 5 cm depth in water. The simulations were made using the DOSRZ Monte Carlo code.

Figure 4.2 Effect of Phantom Size on S_h Measurement
 Measured charge at 5 g/cm² depth in polystyrene miniphantom (mp) with 1.0, 1.5 and 2.0 g/cm² radius (r) for 6 MV (a) and 18 MV (b) photon beams.

Figure 4.3 Effect of Phantom Size on S_h Measurement

Head Scatter factors vs side of a square field for 6 MV (a) and 18 MV (b) photon beams. Measurements were made at 5 g/cm² depth in 3 polystyrene miniphantoms with radii (r) of 0.5, 1.0 and 2.0 g/cm² and with 3 brass build up caps of side-wall thickness (t) of 0.1, 0.5 and 3.5 g/cm². The head scatter factors are normalized to the value of 10 x 10 cm² field.

Figure 4.4 Effect of Phantom Size on S_h Measurement for ^{60}Co Beam

Head scatter factor vs side of square field. Measurements were made at 5 g/cm² in 3 polystyrene miniphantom (mp) with radii (r) of 1.0, 1.5 and 2.0 g/cm². The fourth curve (No mp) is for the case where the ionization chamber was without buildup.

Figure 4.5 Head Scatter Factor vs Side-Wall Thickness

Head scatter factor as a function of brass build-up cap side wall thickness for 6 (+) and 18 MV (•) beams. Results are for 6x6 and 20x20 cm². Note the measurement at 0 side wall thickness was done without any build-up caps present. For clarification the insert is the same data plotted at higher resolution and with the 0 thickness point removed.

Figure 4.6 Head Scatter Factor vs Miniphantom Radius

Head scatter factor vs polystyrene miniphantom radius for the 6 (+) and the 18 MV (•) beams. Results are for 6x6 and 20x20 cm². Note the measurement at 0 size radius was done without any miniphantom present. For clarification the insert is the same data plotted at higher resolution and with the 0 thickness point removed

4.4 Backscatter Factor Measurements Using the FeedBack Loop .

The contribution to the measured value of S_h by backscatter from the collimator jaws into the linac ionization chamber was measured using the “dose rate in open loop method” as described in section 3.5.1. These measurements produced a null result in that there was no observable difference between open and closed loop operation. Both conditions showed the same field size dependence of the dose rate as a function of field size.

4.5 Backscatter Factor Measurements Using the Target Current

The role of backscatter into the linac ionisation chamber was also examined by measuring the total charge deposited into the bremsstrahlung target per monitor unit delivered as a function of field size. The total charge deposited in the bremsstrahlung target was collected across a capacitor and measured as a voltage. In these experiments, each measurement point represents the charge deposited in the target per 100 monitor units delivered. Repeated voltage measurements of a control field size during the experiment produced a standard deviation of 0.1% of the mean readings.

The charge collection data are presented in figure 4.7 for a 6 MV photon beam. This shows that the variation in charge deposited in the bremsstrahlung target (and hence variation in bremsstrahlung production) is less than 0.15% when the radiation field size is changed from 4 x 4 to 40x 40 cm². For comparison the change in head scatter factor

measured in a polystyrene miniphantom for the same change in field size is shown and can be seen to change by approximately 8%. The same measurements were repeated at 18 MV (not shown) and produced similar results.

4.6 S_h and Beam Energy

S_h was measured using the 1.5 cm radius polystyrene miniphantom on the central axis for one linear accelerator at two different beam energies. It should be noted that during clinical operation, when beam energy is changed, the flattening filter is changed. In order to observe changes in S_h as a function of energy two measurements were made, with and without flattening filter. In the former case the clinically relevant changes in S_h can be observed but cannot be solely attributed to energy. In the latter case the observed changes, although not clinically relevant, can be attributed to energy. This data is shown in figures 4.8 a) and b) respectively. As can be seen, the 18 MV beam demonstrates a slightly larger field size dependence than does the 6 MV beam when the change in beam energy is combined with a change in the flattening filters. However, in the case where there is no flattening filter the 18 MV displays a smaller field size dependence than the 6 MV beam. An examination of figures 4.11 a) and b) also demonstrates a larger effect at 18 MV when the measurements are made on and off-axis with flattening filter in place. Repeated output measurements of a control field size during the two experiments (with and without flattening filter) produced standard deviations of 0.1% and 0.11% of the mean readings respectively.

4.7 S_h and Collimator-Exchange Effect

The experimental procedure for investigating the collimator-exchange effects on the value of S_h are described in chapter 3. The results of these studies are presented in figures 4.9 a) and b), (6 and 18 MV beams respectively). The data are presented for four cases in each graph. First the upper jaw is fixed at one field size (either 4 or 8 cm) and then the lower jaw position is changed from 4 to 40 cm. These curves are labelled as 4U or 8U. This is repeated where the lower jaw positions are fixed at 4 and 8 cm while the upper jaw is varied from 4 to 40 cm. These are labelled as 4L or 8L. It can be seen from these data that the value of S_h is a strong function of the position of either the upper or the lower jaws. When the field width (the fixed dimension) was defined by the lower jaw a larger change in S_h with field length was observed.

It can be seen by comparing figures 4.9 a) and b) that similar dependence of S_h on jaw position was observed for both 6 and 18 MV photon beams. Figure 4.10 compares the 6 MV rectangular field S_h data for two linacs, L1 and L2, of similar head design (Siemens MDX serial # 2071 and the Siemens KD2 serial # 1784) and shows that within experimental error the collimator exchange-effect is the same for two different Siemens linacs. Repeated output measurements of a control field size during the two experiments produced standard deviations of 0.1% and 0.15% respectively of the mean readings.

Figure 4.7 Target Current vs Field Size

Head scatter factor (●) (left axis) and back scatter into linac ion chamber (▲) as represented by collected charge (right axis) vs side of square field.

Figure 4.8 Effect of Flattening Filter and Energy on S_h

Head scatter factor vs side of square field in the presence of the flattening filter (a) and when the flattening filter was removed (b) for 6 MV and 18 MV photon beams. Measurements were made at 5 gm/cm² depth with a 1.5 gm/cm² radius polystyrene miniphantom for the data in (a) and with a brass build-up cap of 2.0 g/cm² wall thickness for the data in (b).

Figure 4.9 Collimator-Exchange Effect

Head scatter factors for rectangular fields whose widths were 4 and 8 cm. The widths were defined by either the upper jaws (U) or the lower jaws (L). Measurements were made for 6MV (a) and 18 MV (b) photon beams.

Figure 4.10 Head Scatter factor Comparison between Similar Linacs

Head scatter factor comparison between two similar linacs L1 and L2. Measurements were made for rectangular fields with the upper jaws set at 4,6 and 20 cm. The photon beam energy was 6 MV.

Figure 4.11 Effect of Off-Axis Distance on S_h

Head scatter factor vs side of square for 6 MV (a) and 18 MV (b) beam. Measurements were made with the fields centred on the beam central axis (0 cm OAD) and at 12 cm off-axis distance (OAD). Asymmetric side was defined by the upper jaws.

4.8 Behavior of S_h as a Function of OAD.

Figures 4.11 a) and b) (6 and 18 MV beams respectively) each show measured head scatter factors as a function of field size for two different off-axis distances, 0 and 12 cm. It can be seen that the field size dependence for the 18 MV beam is greater than for the 6 MV beam. Further, it can be seen that for both energies the field size dependence of S_h is reduced when measured off axis.

Figures 4.12 a) and b) (6 and 18 MV beams respectively) graph the family of curves showing the change in S_h as a function of off-axis distance for different square field sizes. The asymmetric sides were defined by the upper jaws. These data are normalised to a 10 x 10 cm² field at each OAD. It is important to note that S_h is only a strong function of off-axis distance for small field sizes. For field sizes greater than 10 x 10 cm² the OAD dependence is not clinically significant. These measurements were repeated with the lower jaws now defining the asymmetric sides and negligible difference in the results was observed.

To further study the linac dose behaviour, in-air miniphantom measurements were made of the off-axis ratio for different size fields at different distances off-axis. This data is shown in figures 4.13 a) and 4.13 b) (6 and 18 MV beams respectively). Shown for reference are the open beam dose profiles measured in-air with the miniphantom for a 40 x 40 cm². Data are shown for fields of 4 x 4, 10 x 10 and 20 x 20 cm². The behaviour of this data is interesting. For both 6 and 18 MV beams the small fields produce the largest OAR

values with increasing off-axis distance. For fields equal to and greater than $10 \times 10 \text{ cm}^2$ the OAR data closely mimic the open beam behaviour.

Figures 4.14 a) and b) are similar to those of figures 4.13 a) and b), except that they are made in a full water phantom. Again, the small fields produce the largest OAR values with increasing off-axis distance for both photon energies. However, in contrast to the miniphantom, measurements of the open beam profile produced the smallest OAR with increasing off-axis distances. The data shown are for the Siemens KD2 (serial # 1784). The Siemens MDX (serial # 2071) (data not shown) displayed similar behaviour. Repeated output measurements of a control field size during the in-air (miniphantom) and in the water experiments produced standard deviations of 0.09% and 0.12% respectively of the mean readings.

4.9 The Influence of the Flattening Filter on the Measured Value of S_h

Figures 4.15 a) and b) (6 and 18 MV) show the measured central axis S_h values for the Siemens KD2, (serial # 3333), with and without the flattening filter in place. For the 6 MV beam it can be seen that with the flattening filter in place the ratio $S_h(40 \times 40) / S_h(4 \times 4) = 1.074$. When the flattening filter is removed this ratio becomes 1.037. Similarly for 18 MV, the ratio with the flattening filter in place is 1.087 as compared to 1.023 without filter. Thus it can be seen that for both 6 and 18 MV the presence of the flattening filter does have a very large influence on the magnitude and field size dependence of S_h .

Figure 4.12 Family of S_h Data as a Function of Off-Axis Distance

Head scatter factor for various square fields as a function of off-axis distance .
Measurements were made at 5 g/cm² depth for 6MV (a) and 18 MV (b) with a 1.5 g/cm² polystyrene miniphantom . Asymmetric sides were defined by the upper jaws.

Figure 4.13 In Air Off-Axis Ratio for Asymmetric Fields

In air off-axis ratio for asymmetric square fields for 6 MV (a) and 18 MV (b) photon beams. Dotted line is the open beam profile for the 40x40 cm² field. All measurements were made with the polystyrene miniphantom.

Figure 4.14 In Water Off-Axis Ratios For Asymmetric Fields

In water off-axis ratios as a function of off-axis distance for the 6MV (a) and for the 18 MV (b) photon beams . Measurements are for 4x4, 10x10 and 20x20 cm² fields. Dotted line is the open beam profile for 40x40 cm² .

Figure 4.15 Effect of Flattening Filter on S_h

Comparison of head scatter factors measured with and without the flattening filter for 6 MV (a) and 18 MV (b) beams. The square fields were centered on the central axis. A brass build-up cap with 2 g/cm² side wall thickness was used in the measurements.

It also appears that, without the flattening filter, the field size dependence of S_h for the 6 MV beam is significantly greater than for the 18 MV beam. However, when their respective flattening filters are introduced, the field size dependence of S_h for the clinical 18 MV beam becomes greater than that of the 6 MV beam.

Head scatter factors were also measured off-axis without a flattening filter present using a brass build-up cap. This data is presented in figures 4.16 a) and b) (6 and 18 MV respectively) which show the measured S_h values for various field sizes at different distances off-axis without flattening filter. The effect of OAD on S_h when there is no flattening filter is significantly different than the OAD effect when the flattening filter is present as can be seen by comparing this data to that of figures 4.11 a) and b). When the flattening filter is present the maximum change in S_h occurs on the central axis. At 6 MV there does not appear to be much difference between on and off axis data, but for the 18 MV beam, the S_h change with field size is greater off-axis than on-axis when the flattening filter is removed.

Measurements were also made of the off-axis ratio in the absence of the flattening filter. Figures 4.17 a) and b) (6 and 18 MV respectively) are graphs of the measured data in-air (miniphantom) of how the output at a field centre changes as a function of that field's off axis distance in the case where the flattening filter was removed. This data is shown for fields of 4 x 4, 6 x 6, 10 x 10, and 20 x 20 cm². Also shown is the open beam profile measured with a brass build-up cap for a 40 x 40 cm² field. Within the experimental error, there is no difference between the 5 cm off-axis values for all field sizes and the open beam

data at both 6 and 18 MV. At 10 cm off-axis there is an observable difference between the small fields and the open field profile as can be seen in table 3.3 which is the ratio of the small field to open field off-axis ratio.

Table 4.2 Off-Axis Ratios as a Ratio of the 40x 40 cm² Open Beam Profile at 10 cm Off-Axis

Energy	4 x 4	6x6	10 x 10	20x20
6 MV	.992	.993	.996	.999
18 MV	.983	.985	.994	.998

What should be noted here is the difference between the behaviour with and without the flattening filter. When the flattening filter is present the difference (see figures 4.11 and 4.13) between the small field and open beam profile is greater, but more importantly the difference increases with larger field size, while in the case without the flattening filter the difference decreases with increasing field size. Similar results (not shown) were found for the relative output factor ($S_h \times S_p$) measured in-water.

Repeated output measurements of a control field without the flattening filter produced a standard deviation 0.11% of the mean readings.

Figure 4.16 Head Scatter Factor Without Flattening Filter

Head scatter factors vs side of square with no flattening filter present in the 6 MV (a) and the 18 MV (b) beam. Fields were centered at the central axis (0 cm OAD), 5 and 10 cm OAD. A brass build-up cap with 2.0 gm/cm² side wall thickness was used in the measurements.

Figure 4.17 In Air Off-Axis Ratio with Flattening Filter

In air off-axis ratios as a function of off-axis distance without the flattening filter being present in the 6MV (a) and in the 18 MV (b) photon beams. Measurements are for 4x4, 10x10 and 20x20 cm² fields. The solid line is the open beam profile for 40x40 cm². A brass build-up cap of 2.0 g/cm² side wall thickness was used in the measurements.

4.10 Selection of Energy and Modelling of The Flattening Filter in Monte Carlo Calculations

In order to confirm that the Monte Carlo generated spectrum reflects the radiation characteristics of the measured 6 MV photon beam, the correct electron beam energy incident upon the bremsstrahlung target should be chosen. In addition the head components, in particular the flattening filter, should be modeled accurately.

In this work 3 electron energies were tested, 6.0, 7.0 and 7.5 MeV. The percentage depth dose for the photon beams produced by each of these electron beams was compared to the measured 6 MV depth dose curve. Figure 4.18 shows the difference between the measured and calculated values. It can be seen that an incident electron beam of 7.0 MeV gives the best results. Hence a 7.0 MeV electron beam incident on the bremsstrahlung target is used in all subsequent Monte Carlo simulations of the 6 MV photon beams from the Siemens KD2.

To verify that the head components were properly modelled, the off-axis ratios (OAR) in-water derived from Monte Carlo simulations, as explained in section 3.8.2, were compared with those data obtained from a 40 x 40 cm² beam dose profile. As expected the OAR were found to exhibit significant dependence on the flattening filter design. A 0.3 cm change in parts of the filter thickness produced approximately a 12 % difference in the magnitude of the OARs. However the quantities of interest in this work, the primary and the scatter fluence, were normalised to the corresponding total fluence. In this form they do

not appear to be sensitive to this small modification in the flattening filter thickness, with a maximum change of only 1.0% from nominal values. In this work the flattening filter was adjusted to produce OAR values to within 3% of the measured beam profile. These adjustments were mostly incorporated at the filter peripheries and a maximum change of 0.2 cm from the nominal manufacture specified thickness was needed. Figure 4.19 presents a comparison between the measured and Monte Carlo determined OAR for water and it shows the agreement to be within 3%.

4.11 Monte Carlo Generated Photon Spectra for Various Head Components

The Monte Carlo user code ACCEL was used to generate the total and primary photon spectra (differential in energy) for a 6 MV beam from the Siemens KD2 linac head at 100 cm SAD. This was done initially for the treatment head with only the bremsstrahlung target and the window in place. Air is always considered to be between the target and the scoring region. These spectra were calculated for various off-axis angles. The calculations were then repeated with the successive addition of individual head components including the primary collimator, the electron beam stopper, the flattening filter, the mirror and the monitor chamber. Finally, the secondary collimators were added to the simulation model. From these data the total, the primary and the scatter photon fluence were determined for each of the conditions listed above as a function of off-axis angle.

Figures 4.20 a) and b) display samples of the calculated total fluence and primary fluence spectra respectively for scoring regions at off-axis angles of 2.86° and 9.6° . These angles

represent a 5 and a 17.4 cm off-axis distance. The simulations were made in the presence of all the head components with the exception of the secondary collimator.

As seen in figure 4.20 a) the maximum photon fluence occurs at energies less than 1 MeV. The position of this maximum exhibits a small energy shift towards the lower energy bins at the larger off-axis angles, going from 0.6 to 0.4 MeV as the off-axis angle increased from 2.86° to 9.6° . The fluence/MeV decreases sharply with increasing energy reaching zero above 7 MeV (i.e. energy of target electron beam). The fluence/MeV increases away from the central axis such that at 17.4 cm. (at 100 SAD) the maximum fluence/MeV increases by a factor of two while the total photon fluence (area under the curve) increases by approximately 28%.

Figure 4.20 b) shows the primary fluence spectra which is presented as a ratio of the total fluence in the corresponding energy bin for scoring regions at off-axis angles of 2.86° and 9.6° . As can be seen, most low energy photons scored at 2.86° undergo scatter. At 9.6° fewer of the scored photons are scattered. The portion of the total fluence due to scattered or primary photons appears to be independent of off-axis angle for energy bins above 1 MeV (within statistical error).

In order to describe how different head components affect the energy spectra at on and off-axis positions figures 4.21 a) and b) and 4.22 a) and b) display the primary and scatter photon spectra for scoring regions at 2.86° and 9.6° off-axis angles with various head components in the simulation. The quantities are presented relative to total fluence in the energy bin.

As can be seen in figures 4.21 a) and b), when air alone is between the target and the scoring region, over 95% of the lower energy photons and virtually all of the photons above 1.0 MV did not interact prior to scoring. As components are added into the beam path a larger percentage of photons interact and the probability of interaction increases significantly in the presence of the flattening filter. The largest effect is seen for low energy photons at locations close to the central axis (including the 2.86° scoring region).

In order to more easily observe the effects of adding the various head components into the simulation, the data in figures 4.21 a) and b) are replotted in figure 4.22 a) and b). This displays the relative scatter fluence (1 - relative primary fluence). Examination of the scatter fluence reaching the scoring region indicates that the largest increase in scatter photons occurs near the central axis when the flattening filter is added to the simulation. The primary collimator and the electron beam stopper do have significant effects on the scattered fluence spectra. In terms of this study the relative importance of each component is dependent on the scatter photon energy. In the lower energy regions (≤ 0.7) MeV the addition of the carbon electron beam stopper results in approximately a 15% increase in photon interactions. At higher energy bins the primary collimator produced more scattered photons than the electron beam stopper. Depending on which head component is present in the simulation the photon scatter exhibits important augmentation at extended off-axis distance. In the absence of the flattening filter, a general increase in the number of photon interactions occurs at 9.6° off-axis angle. However at this angle a decrease in the relative scatter in the low energy bins was observed when the flattening filter was present (see

figures 4.22). The effect of adding the monitor chamber and the mirror to the beam path did not significantly alter the total number of photons which interacted prior to reaching the scoring region.

4.12 Fluence and Fluence Weighted Mean Energies for Various Head Components Determined from Monte Carlo Simulations

Figure 4.23 a) and b) present the total fluence and the total fluence weighted mean energy respectively as a function of off-axis angle for the modelled 6 MV head components. Plots are for the case when air alone and when successively individual head components were added between the target and the scoring regions in the following order: First the primary collimator, then the electron beam stopper, then the flattening filter and finally the monitor chamber and the mirror together.

In figure 4.23 a) the total fluence is normalised to the incident target electron beam fluence used in the simulation. As would be expected this figure shows that the total fluence is maximum when only air is present and decreases with the addition of any of the head components between the target and the scoring regions. In the absence of the flattening filter the fluence is seen to be highly dependent on ϕ where the number of photons is greatest in the central scoring regions and decreasing monotonically for $\phi > 4^\circ$ (7 cm OAD).

Figure 4.18 % Depth Dose Difference vs Electron Energy

Difference between measured and Monte Carlo calculated % depth dose for a photon beam generated by 6, 7 and 7.5 MeV electron beams on the bremsstrahlung target. The curves are for a 10 x 10 cm² equivalent field at 100 cm SAD.

Figure 4.19 Off-axis Ratio Comparison

Monte Carlo determined and measured off-axis ratios for 6 MV beam. All head components were present in the simulations. Error bars are $\pm \sigma$.

Figure 4.20 Total and Primary Photon Spectra

Diagram (a) is the total photon fluence spectra arising from a 7 MeV target electron beam.

Diagram (b) is the corresponding primary fluence spectrum shown as a ratio of the total fluence.

Scoring region centres are at 2.86° (•) and 9.6° (•). Error bars represent $\pm \sigma$.

Figure 4.21 Relative Primary Photon Spectra
Primary photon fluence spectra relative to total photon fluence for a 7 MeV incident electron beam at 2.86"(a) and 9.6"(b) from central axis. Plots are for air alone (broken line) and when consecutively the primary collimator (•), the stopper (+), the flattening filter (▲) and the mirror and monitor chamber (solid line) were also added to the beam path.

Figure 4.22 Relative Scatter Fluence Spectra

Scatter photon fluence spectra relative to total photon fluence for a 7 MeV incident electron beam at 2.86°(a) and 9.6°(b) from central axis. Plots are for air alone (broken line) and when consecutively the primary collimator (●), the stopper (+), the flattening filter (▲) and the mirror and monitor chamber (solid line) were also added to the beam path.

When the flattening filter is included in the simulation a preferential attenuation of the photons in the central part of the beam occurs. This attenuation decreases with distance from central axis reaching a minimum at $\phi > 6.2^\circ$. About 60 % of the photons coming through the beam stopper were removed by the flattening filter in the scoring regions at $\phi < 4^\circ$. At $\phi > 6.2^\circ$ the total fluence relative to the central axis scoring region increased by 28%.

Figure 4.23 b) displays the total photon mean energy (total fluence weighted mean energy) as a function of off-axis angle for various added head components. As can be seen in the figure, the mean photon energy is greatest in the central beam area and decreases monotonically for $\phi > 4^\circ$. In all of the scoring regions a hardening effect occurred where an increase in the mean energy resulted as attenuators (head components) were added into the simulations. The mean photon energy increased by about 0.03 MeV when the primary collimator was added. Insignificant energy changes resulted when the electron beam stopper was included. However, the presence of the flattening filter produced important beam hardening which was greatest in the central beam area where the filter thickness was greatest. On the central axis the mean photon energy increased by about 33% to 1.84 MeV and then diminished monotonically at $\phi > 4^\circ$. The addition of the mirror/monitor chamber resulted in a uniform energy increase of about 0.05 MeV.

Figures 4.24 a) and b) display the primary and scattered photon fluences respectively as a function of off-axis angle ϕ reported relative to the total fluence. In all of the cases studied, 89% or more of the fluence was due to primary photons. The portion of fluence

due to scatter increased upon the addition of each of the various head components. The maximum increase occurred when the flattening filter was added. This brought the number of scattered photons to about 9% of the total.

In the absence of the flattening filter the relative fluence (primary and scattered photons) exhibits an important dependence with increased off-axis distance. In this case the number of scattered photons was smaller in the central beam area and increased monotonically with off-axis angle. However the addition of the flattening filter altered the dependence on off-axis distance making the scatter contribution to appear less dependent on angle. The presence of the mirror/monitor chamber resulted in a uniform scatter increase with off-axis distance of about 1% (see figure 4.24 b).

Figures 4.25 a) and b) display the mean energy (fluence weighted) in each scoring region for the primary and scattered photons respectively as a function of off-axis angle ϕ . As shown in figure 4.25 a) the behavior of the primary mean energy with off-axis distance is similar to the total fluence weighted mean energy of figure 4.23 b) under the conditions studied. Figure 4.25 b) indicates that the scattered photon mean energy in all of the scoring regions increases with the addition of most head components. With the exception of the flattening filter the magnitude of energy increase was independent off-axis angle. The electron beam stopper added after the primary collimator produced a small reduction in energy of about 0.07 MeV. The primary collimator introduced a hardening effect of about 0.2 MeV.

Figure 4.23 Total Fluence and Total Fluence Weighted Mean Energy
Total photon fluence (a) and total photon fluence weighted mean energy (b) vs angle for a 7 MeV incident electron beam. Plots are for air only (broken line) and when consecutively the primary collimator ($\bullet$), the stopper ($+$), the flattening filter (Δ) and the monitor chamber and the mirror ($\blacksquare$) were added to the beam path in the Monte Carlo simulations. Error bars are $\pm \sigma$.

Figure 4.24 Primary and Scatter Fluence as a Function of Off-Axis Distance
 Primary photon (a) and scatter photon fluence (b) vs angle from beam central axis for a 7 MeV incident electron beam. Plots are for only air (broken line) between the target and the scoring region and when consecutively the primary collimator ($\bullet$), the stopper ($+$), the flattening filter ($\blacktriangle$) and the monitor chamber and the mirror ($\blacksquare$) were also added to the beam path. Error bars are $\pm \sigma$.

The addition of the flattening filter significantly increased the mean energy (~ 0.35 MeV) in the central regions with smaller increases observed at larger off-axis angles. The introduction of the flattening filter into the beam absorbed some of the scattered photons produced by the electron beam stopper and the primary collimator, making it difficult to assess their contribution to the scoring regions. In order to examine the extent of this effect a Monte Carlo run was first made with air, the electron beam stopper, the primary collimator and the flattening filter between the target and the scoring regions. Then the calculations were repeated for each of these conditions: i) only the electron beam stopper was removed from the simulations, ii) only the primary collimator was removed from the simulations and iii) both the beam stopper and the primary collimator were removed from the simulations. For each case the scatter fluence and its mean energy were determined and the results are presented in figures 4.26 a) and b).

It can be seen from figure 4.26 a) that in the absence of the electron beam stopper a decrease in the scatter fluence occurred. This amounted to a reduction of about 1% and 1.5% of the total photons scored in the central region and at larger off-axis locations respectively. However the removal of only the primary collimator resulted in an increase in the number of scattered photons by about 1.5 to 2.5 % (of the total photons) with the maximum change occurring at the central axis. This changed when both components were absent from the simulations. In this case the scatter decreased to values similar to when only the electron beam stopper was removed.

Figure 4.26 b) depicts the variation in the scattered photon mean energy with off-axis angle under the above two conditions. It shows that little change in the mean energy resulted when only the beam stopper was removed from the simulations. Also little change in energy occurred when both the primary collimator and the electron beam stopper were absent. However when only the primary collimator was removed a decrease of about 0.2 MeV over all the scoring regions was seen.

Figure 4.27 displays the relative scatter photon fluence as a function of equivalent square (side) at 100 cm SAD. The secondary collimator defining the required equivalent squares was introduced into the simulations such that its bottom part was at the level of the upper jaws. It can be seen that the number of scattered photons reaching the scoring regions is dependent on the size of the field. A significant reduction in photon scatter was observed for the small field (9.8 cm equivalent square side) while the largest field (40 cm equivalent square) had similar levels of scatter contribution as produced by the open beam (no secondary collimators). However, the medium size field (26.5 cm equivalent square) introduced a scatter increase of about 0.5% of the total photons on the central and off-axis regions.

In order to assess the dependence of photon scatter on the collimator location, repeat simulations for different field sizes were made with the secondary collimator moved such that its bottom was at the level of the lower jaws. A comparison of the relative scatter and the mean photon energy (total fluence weighted) with field size for the two secondary

collimator positions (upper and lower jaws levels) is displayed in figure 4.28 a) and b) respectively. The scatter portion of the total photon fluence as a function of field size ranges from 4 to 10.3 % and 5.8 to 10.5 % when the secondary collimator was at the level of the upper and lower jaws respectively (see figure 4.28 a). The lower collimator position increased the scatter by about 2% for small fields while for fields greater than $10 \times 10 \text{ cm}^2$ equivalent square the increase was less and amounted to about 0.5% of total photons. This scatter increase caused the mean photon energy to be slightly softer than when the collimator was at the upper jaws level. This effect is illustrated in figure 4.28 b) where a small decrease in mean energy of about 0.01 MeV was observed for all the field sizes when the secondary collimator was at the level of the lower jaws. Figure 4.23 b) also demonstrates that for fields less than $10 \times 10 \text{ cm}^2$ equivalent square the photon mean energy is greatly dependent on field size. The energy is maximum at the smallest field.

4.13 Primary-to-scatter Ratio

Figure 4.29 presents the primary-to-scatter ratios (P/S) of fluence and energy fluence as a function of equivalent square field size along the central axis. The curves display the results for the cases when the scoring region is in-air and the secondary collimator was positioned at the level of the upper and the lower jaws. Only the P/S of energy fluence are shown for the latter case. As can be seen from the plots the P/S ratios for all cases decrease asymptotically with field size and flattens at larger fields. The values for the energy fluence are always larger than the corresponding ratios of the fluences. For fields $< 10 \text{ cm}^2$

equivalent square a significant decrease in the P/S ratio of the energy fluence is seen when the collimator was positioned at the lower jaws level. However this P/S ratio was independent of secondary collimator position for fields $> 22 \text{ cm}^2$ equivalent square.

4.14 Monte Carlo Calculated Head Scatter Factors

Figure 4.30 shows head scatter factors defined as the ratio of fluence or energy fluence vs field size to that of a reference field. The data were determined with the secondary collimator placed at the level of the upper jaws in the simulations and the scoring region was in the polystyrene miniphantom centred along the central axis. The measured S_h (solid line) are also shown for comparison.

As seen in the figure, the agreement between both of the calculated S_h and the measured S_h are close for the smaller fields. For large fields the S_h defined as the ratio of energy fluence produced better agreement (to within 1%) with the measured data than the S_h calculated on the ratio of fluence.

Figure 4.25 Primary and Scatter Mean Energy as a Function of Off-Axis Distance
 Primary photon (a) and scatter photon (b) fluence weighted mean energy vs angle from beam central axis for a 7 MeV incident electron beam. Plots are for air alone (broken line) between the target and the scoring region and when consecutively the primary collimator (●), the stopper (+), the flattening filter (▲) and the monitor chamber and the mirror (■) were also added to the beam path. Error bars are $\pm \sigma$.

Figure 4.26 Flattening Filter Effect on Scatter Fluence Mean Energy
 Scatter photon fluence (a) and scatter photon fluence weighted mean energy (b) vs off-axis angle for a 7 MeV incident electron beam. Air, stopper, primary collimator, and flattening filter were in the beam path (Δ). Only the primary collimator was removed ($\square$). Only the beam stopper was removed ($\bullet$). Error bars are $\pm\sigma$.

Figure 4.27 Scatter Fluence vs Angle as a Function of Field Size

Scatter photon fluence vs angle from the beam central axis for a 7 MeV incident electron beam. Plots are for the conditions when air, stopper, the primary collimator, the flattening filter, the monitor chamber and the mirror are between the target and the scoring region and when the secondary collimators at the level of the upper jaws were added to define a field of 9.8 , 26.5 and 40 cm equivalent square side at 100 cm SAD. Error bar are $\pm \sigma$.

Figure 4.28 Effects of Secondary Collimator Position

Central axis scatter photon fluence relative to total photon fluence (a) and total fluence weighted mean energy (b) vs side of equivalent square field. All head components were present in the Monte Carlo simulations. The fields were defined by the secondary collimator situated at either the level of the upper jaws or the lower jaws. Error bars are $\pm \sigma$.

Figure 4.29 In Air Primary-to-Scatter Ratio vs Field Size

In air primary-to-scatter ratio (P/S) of fluence (▲) and energy fluence (●) vs side of equivalent square for 6 MV beam with the secondary collimators at the level of upper jaws. Only the P/S of energy fluence is shown when the secondary collimator were at the level of the lower jaws. Data were determined from Monte Carlo simulations. Error bars are $\pm \sigma$.

Figure 4.30 Monte Carlo Calculated Head Scatter Factor

In polystyrene miniphantom total fluence (▲) and total energy fluence (+) determined from Monte Carlo calculations vs side of equivalent square for a 7 MeV incident electron beam. Normalization is to the value for the 9.8 x 9.8 cm² equivalent square field. Measured head scatter factors (solid line) are also shown. Error bars are +/- .

Chapter 5 A Model for the Estimation of Head Scatter Factor for Asymmetric Fields

5.1 Overview

A model has been developed by Yu and Sloboda⁶⁰ for the estimation of head scatter factors, S_h , for a wide range of arbitrary photon fields. Their formulation calculates S_h along the beam central axis and has shown good agreement (to within 0.8%) between the predicted and measured data. In this model the radiation source is characterized using two components: [1] a field size independent intense primary source which reaches the point of interest directly without any scatter from the treatment head and [2] a field size dependent secondary x-ray source which accounts for the head scatter contribution to the same point. The latter, termed an extended secondary source, is represented by a relative intensity distribution whose functional form has been determined⁶⁰ subsequent to detailed measurements of x-ray source sizes and distributions for different linacs by Jaffray et al⁶¹

The Yu and Sloboda formulation is restricted by two geometric considerations: [1] the calculation point should lie along the beam central axis and [2] the central axis must be within the open part of the field. These provisos limit its scope in determining S_h for off-axis asymmetric fields.

Here, this model has been extended to obviate the above restrictions. Modifications to the relative intensity distribution function permit the estimation of S_h for asymmetric

fields whose centers lie within and outside the beam central axis.

Before introducing the model for estimating S_h for more general cases of asymmetric fields a critical review of the work by Yu and Sloboda is provided for reference.

5.2 Yu and Sloboda Model for Estimating S_h

In the model proposed by Yu and Sloboda the head scatter factor, S_h (unnormalized), along the beam central axis is given by:

$$S_h = S_{hp} + S_{hs} \quad (5.1)$$

where S_{hp} and S_{hs} are the primary and secondary source contributions, respectively.

The primary contribution represents unscattered radiation from the target that reaches the point of measurement. The secondary source contribution accounts for scatter originating in the treatment head which also reaches the same point of measurement. The scatter in the head is assumed to be predominantly due to photon interactions in the flattening filter. Consequently the model appropriately estimates the latter contribution by representing the scatter as a relative intensity distribution in the plane at the base of the flattening filter as shown in figure 5.1. The fraction of scattered radiation from this plane which can directly reach the point of interest can thus be determined. More rigorously S_{hs} can be approximated by:

$$S_{hs} = \int_{R_{r\theta}} f_s(r) dr d\theta \quad (5.2)$$

where $f_s(r)$ is a radially symmetric function, about the beam central axis, defining the scatter relative intensity distribution in the secondary source plane. $R_{r\theta}$ is the region in this plane visible from the point of measurement as shown in figure 5.2. The form of $f_s(r)$, based on a model proposed by Ahnesjö²² and consistent with measured source distributions obtained by Jaffray et al⁶¹, is defined by:

$$f_s(r) = \begin{cases} k(r) + \frac{g}{0.3}, & r \leq 0.3, \\ k(r) + \frac{g}{r}, & 0.3 \leq r \leq c, \\ \frac{g}{r}, & r > c, \end{cases} \quad (5.3)$$

where $k(r) = 1 - \frac{r}{c}$. r is the radial distance (in cm) of the secondary source from the

central axis as shown in figure 5.1 and the parameters g and c are positive constants

which are prescribed to accurately reflect the relative intensity of the secondary source.

The constant, 0.3 cm in equation 5.3, was introduced to avoid a divergence at $r = 0$.

The term $k(r)$ represents the major portion of the scatter radiation and is considered to be predominantly due to the flattening filter, whose radial dimension is limited by c . The

term, g/r , was included to correct for the increase in scatter for field sizes limited by $k(r)$. This term takes into account the backscatter radiation effects arising from the secondary collimators⁶⁰, forward scatter from the secondary collimators reaching the point of measurement and possibly higher order scatter in the accelerator head whose radial extent is not limited by the primary collimator.

The effect of backscatter radiation into the beam chamber was previously discussed in section 2.5.1. It's contribution to S_h is dependent on the treatment head and the monitor chamber design. In cases where backscatter is significant, it's contribution to the output factor was assumed to be approximately proportional to field size⁶⁰.

In terms of the forward scatter contribution, Ahnesjö²² showed that scatter increased as field size increases. Since the increase was typically small in magnitude over the range of clinically relevant field sizes, this effect could be adequately modeled as a linearly increasing function of field size.

The calculation of S_h was accomplished by evaluating S_{hs} , equation 5.2, and estimating S_{hp} from the ratio of the primary-to-scatter contribution, (S_{hp}/S_{hs}) . This ratio has been determined by several investigators^{6,21,45} and has been shown to be both energy and field size dependent. In estimating S_h , Yu and Sloboda chose the most appropriate values of (S_{hp}/S_{hs}) , c and g to best fit the measured data along the central axis. They determined c and g to be energy independent. They also commented that the latter parameters will be off-axis dependent if their model is extended to estimate S_h for asymmetric fields whose centres are away from the central axis.

5.3 Estimation of S_h for Off-Axis Asymmetric Fields

The Yu and Sloboda model has been extended to estimate off-axis head scatter factors, S_{hoa} , in the center of asymmetric fields. In this case the formulation completely obviates the geometric restrictions imposed in the original model.

Figures 5.3 a) and 5.3 b) depict an asymmetric field with dimensions Y_{oa} and X_{oa} (oa denotes an off-axis position) as defined by the upper and lower jaws at SAD , respectively. The center of this field, O_{oa} , is displaced a distance oa_x and oa_y from the beam central axis in the x -axis and y -axis direction. The area affected by the secondary source distribution, which is visible from O_{oa} , can be determined from the head geometry of the linear accelerator as shown in figures 5.4. This area is defined by Y_{soa} and X_{soa} which are the projections of Y_{Joa} and X_{Joa} respectively onto the secondary source plane. These projections represent the lower and the upper jaw offsets from the field central ray and are given by:

$$Y_{Joa} = \frac{Y_{oa} d_{up}}{2SAD} \quad (5.4)$$

$$X_{Joa} = \frac{X_{oa} d_{low}}{2SAD} \quad (5.5)$$

and hence

$$Y_{soa} = 2Y_{Joa} \frac{(SAD - d)}{(SAD - d_{up})} = k_y \cdot Y_{oa} \quad (5.6)$$

$$X_{soa} = 2X_{Joa} \frac{(SAD - d)}{(SAD - d_{low})} = k_x \cdot X_{oa} \quad (5.7)$$

Figure 5.1 Illustration of the Secondary Source Geometry

The target, primary collimator and the flattening filter. The radial distance 'r' and the angle (θ) are shown at the level of the secondary source.

Figure 5.2 Illustration of the Two Component Source Model

In (a) a field size x and y defined by the upper and the lower jaws which are at d_{up} and d_{low} from the plane containing the primary focal source 'P' respectively. b) The area in the secondary source plane revealed by the jaws to measurement point O_a is delineated by X_s and Y_s . 'd' is the distance of secondary source from 'P'.

where
$$k_y = \frac{(SAD - d)}{(SAD - d_{up})} \frac{d_{up}}{SAD} \quad (5.8)$$

$$k_x = \frac{(SAD - d)}{(SAD - d_{low})} \frac{d_{low}}{SAD} \quad (5.9)$$

d , d_{up} and d_{low} are the distances of the secondary source plane, the top of the upper collimator jaws and the top of the lower collimator jaws from the primary source plane. Figure 5.5 illustrates a two dimensional representation of an asymmetric rectangular field defined at SAD and it's projection onto the secondary source plane as observed from the field center at O_{oa} . The center of the projected field is at $\left[a + \frac{X_{soa}}{2}, b \right]$ from the beam central axis, PO_a . The quantity a is the distance from the central axis to the proximal edge of the open field along the x-axis. The values of a and b can be determined from figure 5.4:

$$a = (oa_x \times \frac{d}{SAD}) - \frac{X_{soa}}{2} \quad (5.10)$$

$$b = (oa_y \times \frac{d}{SAD}) \quad (5.11)$$

5.3.1 Estimation of S_{hoa}

The determination of S_{hoa} is obtained in the following way: Let

$$S_{hoa} = S_{hpoa} + S_{hsoa} \quad (5.12)$$

where S_{hpoa} and S_{hsoa} are the primary and secondary scatter contributions observed at the center of the off-axis asymmetric field respectively.

The estimation of S_{hsoa} can be obtained in an analogous way as S_{hs} , viz. eqn 5.2:

$$S_{hsoa} = \int_{R_{r\theta}} f_{soa}(r) dr d\theta \quad (5.13)$$

where $f_{soa}(x, y)$ is the relative intensity distribution for the secondary source of radiation defined at the level of the flattening filter base and $R_{r\theta}$ is the region in the secondary plane visible from O_{oa} .

Since the geometries associated with off-axis fields are, in general, more complicated than fields incorporating the central axis, the solvability of eqn 5.13 is greatly improved by transforming the integral from polar coordinates to cartesian coordinates.

$$S_{hsoa} = \int_{R_{xy}} f_{soa}(x, y) dx dy \quad (5.14)$$

The form of $f_{soa}(x, y)$ is then given by:

$$f_{soa}(x, y) = \begin{cases} k(x, y) + \frac{g}{r}, & 0.0001 \leq r \leq c, \\ \frac{g}{r}, & r > c, \end{cases} \quad (5.15)$$

where $k(x, y) = 1 - \frac{r}{c}$, $r = \sqrt{x^2 + y^2}$ and the parameters c and g are again prescribed.

Similar to equation 5.3 the form of $f_{soa}(x, y)$ was chosen to preclude any divergence in the intensity distribution function.

S_{hsoa} is evaluated by integrating $f_{soa}(x, y)$ over the region at the base of the filter

bounded by the secondary source seen by the observer and limited by X_{soa} and Y_{soa} (see figures. 5.4 and 5.5). Therefore, S_{hsa} can be expressed as

$$S_{hsa} = \iint_{r \leq c} (1 - \frac{r}{c}) dx dy + \iint_{r \geq 0.0001} \frac{g}{r} dx dy \quad (5.16)$$

The first term in equation 5.16 determines the major portion of scattered radiation from the secondary plane that reaches the measuring point. The influence of this component is limited by c and again its extent depends on the primary photon fluence which passes through the unblocked part of the primary collimator at the level of the flattening filter bottom.

Using figures 5.5 and 5.6 the limits of integration for the first integral in eqn 5.16 can be written as:

$$\iint_{r \leq c} (1 - \frac{r}{c}) dy dx = \overbrace{\int_{Y_L}^{Y_U} dy \int_{X1}^{X2} dx}^{I_1} - \overbrace{\int_{Y_L}^{Y_U} dy \int_{X1}^{X2} \frac{r}{c} dx}^{I_2} \quad (5.17)$$

where Y_L and Y_U are the lower and upper limits of integration in the y-axis direction

The integral, I_1 , is given by:

$$I_1 = \frac{c^2}{2} \sin^{-1} \left[\frac{y}{c} \right] + \frac{1}{2} y \sqrt{c^2 - y^2} - a \cdot y \Big|_{Y_L}^{Y_U} \quad (5.18)$$

Details surrounding the evaluation of I_1 are provided in Appendix A. Similarly, the evaluation of I_2 yields the following:

$$I_2 = \frac{I}{6} \left[\begin{aligned} & y\sqrt{c^2 - y^2} - \frac{2ay\sqrt{a^2 + y^2}}{c} + 2c^2 \sin^{-1}\left[\frac{y}{c}\right] - \frac{a^3 \sinh^{-1}\left[\frac{y}{a}\right]}{c} \\ & + \frac{y^3 \log\left[c + \sqrt{c^2 - y^2}\right]}{c} - \frac{y^3 \log\left[a + \sqrt{a^2 + y^2}\right]}{c} \end{aligned} \right] \Bigg|_{Y_L}^{Y_U} \quad (5.19)$$

Subtracting equation 5.19 from 5.18 yield the solution of 5.17:

$$\iint_{r_{sc}} \left(1 - \frac{r}{c}\right) dy dx = \frac{I}{6c} \left[\begin{aligned} & -6acy + 2cy\sqrt{c^2 - y^2} + 2ay\sqrt{a^2 + y^2} + c^3 \sin^{-1}\left[\frac{y}{c}\right] \\ & + a^3 \sinh^{-1}\left[\frac{y}{a}\right] - y^3 \log\left[c + \sqrt{c^2 - y^2}\right] \\ & + y^3 \log\left[a + \sqrt{a^2 + y^2}\right] \end{aligned} \right] \Bigg|_{Y_L}^{Y_U} \quad (5.20)$$

The limits of integration, Y_L and Y_U , are dependent on the locations of the jaws defining the asymmetric field. The position of these jaws may block part of the secondary source which will effect the extent of scatter that reaches the observation point. This is clearly illustrated in figure 5.6 where the shaded area represents the unblocked part of the secondary source seen from the measuring point.

The limits Y_L and Y_U have been changed to reflect the sample asymmetric field geometries that correspond to different jaw locations. Figures 5.7a through 5.7d depict these conditions and the limits of integration for each case are given in Table 5.1.

The evaluation of eqn 5.17 for a selected configuration (viz. table 5.1) is provided in appendix A.

The second integral in eqn 5.16 can be expressed as:

Figure 5.3 Asymmetric Field Geometry

X_{ua} and Y_{ua} are the asymmetric field dimensions in the isocenter plane along the x-axis and y-axis direction respectively. d_{up} and d_{low} are the distances from the focal source to the top of the upper and lower jaws respectively. PO_{ua} is the axis of the asymmetric field that joins the focal source P and the centre of the field at Y_{ua} . O_{sa} and O_a are the beam central axis points of intersection with the secondary source and isocenter plane respectively.

Figure 5.4 Geometries Used in the Head Scatter Factor Model

X_{soa} and Y_{soa} are the projections of $2 \times X_{Joa}$ and $2 \times Y_{Joa}$ in the plane of the secondary source respectively as observed from the O_{ou} . X_{ou} and Y_{ou} are the asymmetric field dimensions at isocenter along the x-axis and y-axis direction respectively. 'a' is the distance from beam axis (PO_a) to the proximal edge of X_{soa} side as shown in diagram a). 'b' is the distance from Y_{soa} side centre to the beam axis as shown in diagram b). d_{up} and d_{low} are the distances from the focal source to the top of the upper and lower jaws respectively

$$\iint_{\sqrt{x^2 + y^2} > 0.0001} \frac{g}{\sqrt{x^2 + y^2}} dy dx = \int_{Y_L}^{Y_U} dy \int_{X1}^{X2} \frac{g}{\sqrt{x^2 + y^2}} dx \quad (5.21)$$

and as illustrated in figure 5.6 the limits of integration are:

$$Y_L = -\sqrt{c^2 - a^2}$$

$$Y_U = \sqrt{c^2 - a^2}$$

$$X1 = a$$

$$X2 = a + X_{soa}$$

The solution of eqn 5.21 is given by:

$$\int_{Y_L}^{Y_U} dy \int_{X1}^{X2} \frac{g}{\sqrt{x^2 + y^2}} = \left[\begin{aligned} & -g \cdot y \log \left[a + \sqrt{a^2 + y^2} \right] - a \cdot g \log \left[y + \sqrt{a^2 + y^2} \right] + \\ & g \cdot y \log \left[X_{soa} + \sqrt{X_{soa}^2 + y^2} \right] + \\ & g \cdot X_{soa} \log \left[y + \sqrt{X_{soa}^2 + y^2} \right] \end{aligned} \right]_{Y_L}^{Y_U} \quad (5.22)$$

The total scatter contribution, S_{hsoa} , reaching the point O_{oa} is thus given by summing equations 5.20 and 5.22. The primary component, S_{hpoa} , is determined in a similar fashion as that outlined in section 5.2 by using the ratio of the primary-to-scatter contribution, (S_{hpoa}/S_{hsoa}) . Since this ratio is energy, field size and position dependent, then a suitable ratio, as well as the c and g values have been determined to best fit the measured data.

To summarize, for any asymmetric field, S_{hoa} can be estimated according to following scheme:

1. If $0.0001 \leq a \leq c$, S_{hsa} is given by the summation of equations 5.20 and 5.21.
2. If $0.0001 \leq c < a$, S_{hsa} is given by equation 5.21 only.
3. If none of the jaws cross the beam central axis, then the expressions similar to Y_u and Sloboda⁵⁹ were used to calculate the head scatter contributions.
4. When the contribution of the primary source is evaluated, the unnormalized asymmetric field head scatter factor S_{hsa} is calculated according to equation 5.12.
5. At each off-axis calculation point, O_{oa} , the calculated data are normalized to the value of the $10 \times 10 \text{ cm}^2$ field at that location and the head scatter factor is thus obtained.

The values of d , d_{up} and d_{low} , discussed in section 5.3.1, have been obtained from the Siemens KD2 linac engineering drawings to be 9.86, 20.72 and 28.34 cm

Table 5.1 Integration Limits for the Different Jaw Locations

Figure #	Jaw Location		Integration Limits	
	Y1	Y2	Upper (Y_U)	Lower (Y_L)
5.7a	$< -\sqrt{c^2 - a^2}$	$> \sqrt{c^2 - a^2}$	$\sqrt{c^2 - a^2}$	$-\sqrt{c^2 - a^2}$
5.7b	$> -\sqrt{c^2 - a^2}$	$< \sqrt{c^2 - a^2}$	$b + \frac{k_y \cdot Y_{oa}}{2}$	$b - \frac{k_y \cdot Y_{oa}}{2}$
5.7c	> 0	$> \sqrt{c^2 - a^2}$	$\sqrt{c^2 - a^2}$	$b - \frac{k_y \cdot Y_{oa}}{2}$
5.7d	$< -\sqrt{c^2 - a^2}$	> 0	$b + \frac{k_y \cdot Y_{oa}}{2}$	$-\sqrt{c^2 - a^2}$

Figure 5.6 Geometry Used in Evaluating S_{hoa}
 An illustration of the limits used to determine the scatter contribution defined by S_{hoa} . A top view of the asymmetric rectangle whose four corners are shown in the secondary source plane. The radius 'c' determines the extent of the relative intensity distribution.

Figure 5.7 Limits for the Various Asymmetric Field Geometries
 Illustrations of the different asymmetric geometries used in determining the integration limits Y_L and Y_U .

5.4 Results

Calculations of S_{hoa} were performed for 6 and 18 MV photon energies using asymmetric square and rectangular fields. The centers of these fields were located at positions ranging from 2 to 12 cm off-axis.. For each off-axis distance (OAD) the primary-to-scatter ratios ($S_{hpoa}/S_{hs oa}$) were determined to best fit the measured data within $\pm 0.4\%$. The fact that the model parameters become OAD dependent is discussed in chapter 6. For all field geometries and photon energies tested, the parameter c was 1.8 cm. This value produced a maximum deviation of 0.7% between estimates of head scatter factor and measured data.

Figures 5.8 and 5.9 indicate the values of g and $S_{hpoa}/S_{hs oa}$ respectively which yield the best estimate of S_{hoa} as a function of OAD. As seen in figure 5.8 the g value is generally small and is dependent on distance from the center. It displays a slight energy dependence up to 10 cm OAD where after the difference in g values between the 6 and 18 MV photon beams is large. Regarding the primary-to-scatter ratio, figure 5.9 shows this ratio to be a monotonically increasing function with OAD and its magnitude decreases with increasing photon energy for a given OAD.

A comparison of measured and estimated values of S_{hoa} for square fields using 6 and 18 MV photon beams is provided in figures 5.10 and 5.11. The results are presented for asymmetric fields, defined by the upper jaws, centered at 4 and 12 cm OAD and also for symmetric fields centered on the central axis. The values ($S_{hpoa}/S_{hs oa}$), g and c used by the

model are listed for each field center position. The data shown in figures 5.10 and 5.11 clearly shows very good agreement between the estimated and measured values with a maximum discrepancy of 0.7%. This level of error occurs at extended (>10 cm OAD) distances from the center. Results for other fields at different OAD show similar agreement. Again for these cases an optimal (S_{hpoa}/S_{hsoa}), c and g were determined. An attempt was made to reduce the error at 12 cm OAD to within 0.4% of the measured data and this required new values for the parameters including c . In this case c was changed to 1.65 cm. Figures 5.10 d and 5.11 d show the new S_{hoa} estimates at the 12 cm OAD for 6 and 18 MV beams respectively.

The model was also applied to asymmetric fields defined by the lower jaws of the collimator for both energies. A sample of these results is shown in table 5.2 for a 6 MV beam with square fields centered at 5 cm OAD. Here the calculated and measured values agreed to within 0.2%. Similar calculations were carried out for other off-axis distances and again reveal excellent agreement with measured data.

Estimates of S_{hoa} for rectangular fields at 10 cm OAD using a 6 MV beam were performed (the asymmetric side of the rectangle here is defined by the upper jaws). The results of this calculation are presented in table 5.3 and demonstrate better than 0.4% agreement between the estimated and measured data.

The ability of the model to predict the collimator-exchange effect was investigated for both 6 and 18 MV photon beams. For this situation, S_{hoa} was measured and calculated for similar rectangular fields, but their lengths and widths were alternately defined by the

upper and the lower collimator jaws. Tables 5.4 and 5.5 supply results of the collimator-exchange for rectangular fields centered on the central axis for 6 MV and 18 MV beams respectively. In both cases the results show good agreement to within 0.3% between the measured and estimated data.

Table 5.2 Measured and Estimated S_{hoa} for Square Fields from the 6 MV Beam Whose Center is Located at 5 cm OAD

Field Size $X \times Y$ (cm ²)	Measured S_{hoa}	Estimated S_{hoa}	Ratio
6x6	0.977	0.979	1.002
8x8	0.99	0.992	0.998
15x15	1.013	1.012	1.001
20x20	1.016	1.017	0.999
30x30	1.021	1.024	0.998

* Asymmetry defined by the lower jaws

Table 5.3 Measured and Estimated S_{hoa} for Square Fields from the 6 MV Beam Whose Center is Located at 10 cm OAD

Field Size $X \times Y^*$ (cm ²)	Measured S_{hoa}	Estimated S_{hoa}	Ratio
10x4	0.974	0.977	0.997
20x4	0.977	0.979	0.998
30x4	0.977	0.981	0.996
10x6	0.986	0.985	1.001
20x6	0.989	0.989	1.0
30x6	0.99	0.991	0.999

* Asymmetry defined by the upper jaws

Table 5.4 Comparison Between Central Axis Measured and Estimated S_h for Rectangular Fields from the 6 MV Beam

Field Size XxY (cm ²)	Measured S_h	Estimated S_h	Ratio
6x4	0.964	0.962	1.002
4x6	0.9621	0.961	1.001
10x4	0.976	0.975	1.001
4x10	0.968	0.968	1.0
40x4	0.984	0.983	1.001
4x40	0.97	0.97	1.0
10x5	.983	.984	0.998
5x10	0.975	.976	0.998
20x5	.9901	.991	0.999
5x20	0.978	0.977	1.001

Table 5.5 Comparison Between Central Axis Measured and Estimated S_h for Rectangular Fields from the 18 MV Beam

Field Size XxY (cm ²)	Measured S_h	Estimated S_h	Ratio
10x4	0.961	0.958	1.003
4x10	0.971	0.971	1.0
20x4	0.962	0.964	0.998
4x20	0.979	0.977	1.002
30x4	0.963	0.963	1.0
4x30	0.979	0.978	1.001

Figure 5.8 Variation of the Parameter 'g' with Off-Axis Distance for 6 MV and 18 MV Beams

Figure 5.9 Variation of the Primary-to-Scatter Ratio with Off-Axis Distance for 6 MV and 18 MV Beams

6 MV

Figure 5.10 Comparison of Calculated and Measured Head Scatter Factors

Comparison of calculated (broken line) and measured (+) head scatter factors for 6 MV beam. Data are shown for positions at central axis (a), 4 cm (b), 12 cm (c) and 12 cm (d) off-axis distance. The values of the primary-to-scatter ratio, g and c are shown in each plot.

18 MV

Figure 5.11 Comparison of Calculated and Measured Head Scatter Factors

Comparison of calculated (broken line) and measured ($\pm$) head scatter factors for 18 MV beam. Data are shown for positions at central axis (a), 4 cm (b), 12 cm (c) and 12 cm (d) off-axis distance. The values of the primary-to-scatter ratio, g and c are shown in each plot.

Chapter 6

Discussion

6.1 Requirement for lateral electronic equilibrium in the measurement of S_h

It is generally accepted that total electronic equilibrium is required in order to make valid dosimetric measurements with an ion chamber^{18,58}. This results in a problem for the measurement of tissue air ratio (TAR) like data for high energy photons since the build-up material thickness required for electronic equilibrium is such that the phantom scatter becomes significant. Consequently it is not possible to measure “in-air” doses for very small field sizes.

In this work this problem is examined. Electronic equilibrium can be thought of as consisting of two parts: the equilibrium from forward scatter – generally referred to as build up (i.e. electronic fluence build up), and lateral electronic equilibrium (**LEE**). Two methods of measurement were used to examine the effect of phantom dimension on S_h measurement: that described by van Gasteren et al³⁹ with a tissue equivalent miniphantom and the use of small coaxial buildup caps made of high z material (brass). Monte Carlo studies were performed to determine the phantom radius, r_{LEE} , at which **LEE** was required in a miniphantom of the van Gasteren design or for a high Z brass cap. In both cases the thickness (or depth) proximal to the beam was sufficient to provide full forward electronic equilibrium. These results are shown in figure 4.1 for 5 different photon beams and are summarized in table 6.1. This table lists the minimum thickness,

r_{LEE} , of phantom wall required for a Bragg-Gray cavity type measurement for several different beam energies. The table also shows the TPR_{10}^{20} ratio which was reported by Kosune and Rogers⁶² as a means of quantitatively describing the beam quality. The value of r_{LEE} for the 6 MV beam which was calculated in this work is consistent with that reported by Bjärngard et al⁶³.

Dosimetric measurements of S_h were then performed in a polystyrene miniphantom and with a brass build up cap. A series of different phantom wall thicknesses were used. The results of these measurements are shown in figures 4.5 and 4.6. From this it can be seen that S_h can be determined accurately when the phantom is smaller than that required for LEE. There are two principal implications from this:

1. Clinically valid measurements of S_h can be made down to very small field sizes
2. Lateral electronic equilibrium is not required for the determination of S_h

The question then is why should measurements made under non-LEE conditions provide valid results. The answer most likely lies in the fact that S_h is in fact reported as a ratio of measurements at two different field sizes. Remember that the ion chamber response is due to the total ionization within the chamber cavity. This total will be due to the photon fluence impinging upon the phantom and to contaminant electrons reaching the ion chamber from the linac head. The electron contamination is produced by the interaction of photons with the head components. Although the ionization produced in the chamber by photons from the linac head is field size dependent, it is likely that the chamber response due to contaminant electrons is small compared to that from the photons and only weakly field size dependent. This effect is true provided the chamber is

surrounded with enough material to stop the majority of contaminant electrons. Thus the reported value of S_h will be the ratio of two terms both containing a relatively large field size dependent term (due to photon fluence) plus a much smaller and relatively field size independent term due to contributions from the contaminant electrons. As such the second term will have minimal effect on S_h ratio.

In the case when the chamber is bare or surrounded by too small a brass side-wall thickness (or miniphantom diameter) the contaminant electrons will have a much greater influence on the chamber response which increases with field size^{64,65}. This results in a much higher chamber reading for larger fields and leads to the measured S_h to be smaller than the plateau values for fields less than 10 x 10 cm². For larger size fields the reverse occurs and the S_h values are greater than the plateau value as shown in figures 4.5 and 4.6. When the thickness of material around the chamber is large enough to stop most of the contaminant electrons, a plateau in S_h value will be reached for each field size as shown in figures 4.5 and 4.6. At this condition any changes in S_h with field size is a reflection of the actual difference in the amount of photon head scatter.

As the brass side-wall thickness or the polystyrene diameter is increased beyond the plateau range, scatter from the phantom becomes important. Consequently, the chamber reading will now include the integration of scatter contributions which originated from the treatment head and the phantom.

The important question is what thickness of material is sufficient to stop all (or most) of the contaminated electrons that enter the chamber from the top surface and from the side-walls. In order to answer this we need to know the energy of the electrons entering the miniphantom or the brass cap.

The Monte Carlo ACCEL code was used to calculate the mean electron energy for 6 and 18 MV x-rays beams from the Siemen's linac head (serial # 1784) and it was estimated to be 1.6 ± 0.2 and 4.1 ± 0.3 MeV respectively. The scoring region was for a 2 cm radius and 1 cm thick disc of air at 100 cm distance from the source. All of the head components with the exception of the secondary collimators were present in the simulations. The majority of the Compton secondary electrons produced in the head will have small scattering angle and hence will enter from the phantom top. A fraction of these contaminant electrons will enter the phantom from the side-walls. In order for this to happen the electrons should experience multiple scatter events in air or head components and be directed towards the phantom sides. As a result their mean energy will be less than from those entering from the top and a smaller material thickness will stop them.

Recall that the chamber was placed at an equivalent depth of 5 g/cm^2 . This depth is sufficient to stop contaminant electrons that enter from the phantom top with energies up to 10 MeV. A brass side-wall thickness of about 0.7 g/cm^2 or greater was shown in this work to produce no change in S_h . This indicates that this wall dimension has reduced the contaminant electron contribution to a relatively small level such that the chamber

response is now dominated by ionizations from the secondary electrons produced by the photon fluence in the phantom.

When the effects of electron contamination are eliminated, the S_h values measured with the polystyrene miniphantoms and with the brass caps agreed to within 0.5%. This indicates that the spectral changes (photons and electron) resulting from the presence of the higher Z brass have little effect on the measured relative quantity S_h .

Thus **LEE** is not required in S_h measurements as long as the effects of electron contamination are eliminated. The reported work^{26,39} on S_h measurements under lateral disequilibrium conditions can now be justified and brass caps or polystyrene miniphantoms can be used for S_h measurements provided the wall thickness or miniphantom diameter is large enough to stop the contaminant electrons.

6.2 Backscatter Radiation to The Monitor Chamber

It is demonstrated in figure 4.7 that for the linacs used in this work and within the experimental random errors, backscatter radiation (BSR) from the collimator jaws to the monitor chamber does not play a role in the determination of S_h . This agrees well with the results of Dunscombe et al⁶ for a 6 MV beam obtained by disabling the feedback control of a similar linac model.

Table 6.1 The Monte Carlo Calculated Values of r_{LEE} * for Various Photon Beams

Beam	TPR ₁₀ ²⁰	r_{LEE} (g/cm ²)
⁶⁰ Co		0.6
6 MV	0.670	1.3
10 MV	0.732	1.7
15 MV	0.765	1.9
24 MV	0.805	2.1

* r_{LEE} is the minimum beam radius to achieve complete lateral electron equilibrium in a water phantom.

This negligible BSR effect on the monitor chamber could be attributed to either:

1. No BSR reaches the monitor chamber sensitive volume.
2. There is backscatter radiation but it is independent of field size.

Note that the BSR is produced by the collimator jaws and as such should be dependent on the position and location of these jaws. Thus it is assumed backscatter effects are field size dependent and condition 2 above is invalid.

The backscatter radiation from the collimator jaws consists of electrons and low energy photons. From Klein-Nishina⁵⁸ calculations using 1 MeV incident photon energy, the differential cross section of scattered photons at angles $> 90^\circ$ is less than 10% of the value

for photons scattered at angles $< 5^\circ$. As the incident photon energy increases the number of large angle scattered photons becomes even smaller⁵⁸.

The mean energy for the 6 and 18 MV beams modeled in this work is about 1.9 and 4.5 MeV respectively. For photons from the linac bremsstrahlung target whose energies are greater than 0.511 MeV (electron rest mass) the maximum Compton photon backscatter energy from the collimator jaws is 0.255 MeV. Thus one will expect the number of backscatter photons to be relatively small and that their mean energy will be less than 0.255 MeV. Consequently a small thickness of material should be sufficient to significantly reduce the levels of back scatter radiation (photons and electrons) reaching the monitor chamber.

Luxton⁴³ et al reported that a 0.29 g/cm^2 acrylic ($\rho = 1.19 \text{ g/cm}^3$) sheet covering the downstream portion of the monitor chamber would absorb 75 % of the backscatter radiation from a 23 MV photon beam. The dose monitor chamber for each of the linacs used in this work is situated at 10 cm above the upper collimator jaws and has a ceramic wall thickness of 0.7 g/cm^2 ($\rho = 3.57 \text{ g/cm}^3$). The combination of the chamber location and its wall thickness probably account for the observation in this work that BSR effects are negligible. Hence, the forward photon head scatter can be considered to play the most important role in the field size dependence of the head scatter factor and any consideration of the BSR effect will be ignored in the rest of this work.

6.3 S_h and It's Influencing Factors

The measured behavior of S_h as a function of photon energy is demonstrated in figure 4.8 where two sets of data for 6 and 18 MV beams with and without the flattening filter are shown. In the absence of the flattening filter the 6 MV photon beam shows greater S_h dependence on field size than the 18 MV. Conversely, when the flattening filter was placed in the beam path, the opposite is observed. The 18 MV S_h data now (figure 4.8 a) show the greatest field size dependence. The larger field size dependence of the 6 MV photons (in the absence of the flattening filter) is to be expected. It can be attributed to the larger interaction cross section and larger mean scatter angle of the 6 MV photon beam compared to the 18 MV beam.

When the flattening filter was removed the only difference in the head assembly between the two energies was the presence of an additional electron stopper, which is made of aluminum, in the path of the 18 MV beam. Assuming the Compton effect is the dominant mechanism of interaction in the remaining treatment head components then the photon scattering angles become more forward biased with increasing incident photon⁵⁸ energy. Thus the 6 MV beam scattered photons will be more diffuse than the 18 MV resulting in more photons reaching the central axis from the beam periphery with increasing field size. Consequently the scatter contribution at the center will exhibit a larger increase with increasing field size. This results in a greater S_h field size dependence for the 6 MV than for the 18 MV beam.

This behavior was verified by using the ACCEL Monte Carlo code to determine the change in scattered photon fluence with field size in the polystyrene miniphantom (3 cm diameter) for the photon beams produced by the Siemens linac (serial # 1784). All head components with the exception of the flattening filter were present in the simulation. The scoring region was a disc of 1 cm radius and 1 cm thick situated on the central axis at a depth of 5 g/cm² at 100 cm SAD

Two field sizes were simulated for both the 6 and 18 MV photon beams. For the 6 MV beam, the scatter ratio (scatter fluence /total fluence) went from 0.185 to 0.217 with increasing field size. In comparison the relative scatter for the 18 MV beam went from 0.15 to 0.16 for the same increase in field size from 4 x 4 to 10 x 10 cm². The calculation standard deviation for the ratios was < 0.8%.

Thus, it has been shown both experimentally and by Monte Carlo simulation that when energy is the only variable, S_h for 6 MV photons demonstrates a greater field size dependence than for 18 MV and this is consistent with basic Klein -Nishina results. However, the clinical photon beams exhibit a different behavior. In this case, the 18 MV beam demonstrates a larger field size dependence than does the 6 MV beam (see figure 4.8). The only difference in this case being that each of the two beams has a dramatically different field flattener in the beam (See figure 6.1 comparing the two filters).

Note that these experimental observations were verified by Monte Carlo simulation with the appropriate flattening filters in place. In this case the 6 MV scatter ratio changed from 0.175 to 0.22 when the field size was changed from 4 x 4 to 10 x 10 cm², while the 18 MV scatter ratio went from 0.15 to 0.20 for the same field size change.

It then seems likely that change in S_h field size dependence can be attributed to the flattening filter and indeed that the flattening filter can be considered to have a dominant influence on S_h .

The difference in the scatter behavior (S_h) with the flattening filter present must be attributable to a physical process. Consider that to 1st order the flattening filter acts as a secondary source of radiation (scatter) which is proportional to the mass of flattening filter visible to the observer (measurement point).

Other workers ^{6, 38} have introduced a similar concept but restricted the model to consider the area of a predetermined scatter intensity distribution visible to the observer. They have then attributed the principal part of S_h field size dependence to be proportioned to the area of the flattening filter visible at the observation (measurement) point. Ahnesjö²² determined the amount of scatter reaching a calculation point from the visible part of the filter by considering the first-order Compton scatter released per unit filter area from a finite filter element. A “generic” precalculated filter shape was used.

In the model introduced here, it is assumed that the total scatter fluence is directly proportional to the mass of the flattening filter, which is irradiated. This would be valid if all interactions were Compton and if there was no absorption of scatter photons by the flattener. Details of the calculation are shown in appendix B.

Figure 6.2 depicts the total mass of flattening filter visible to the observer on the central axis as a function of square field size, for both the 6 and 18 MV field flatteners.

What can be seen is that the 18 MV filter provides a much larger scattering mass (source) than does the 6 MV filter, and that the rate of change of mass with field size is greater for the 18 MV filter. Further, for both the 6 and 18 MV beams, the collimator/filter geometry is such that the mass visible to the observer is constant for field sizes greater than $20 \times 20 \text{ cm}^2$.

Thus, it can be concluded that for the central axis S_h , the flattening filter acts as one of the dominant sources of scatter and that the scatter is proportional to 1st order to the mass of filter visible from the point of interest. Further, because the 18 MV flattening filter is much more massive than the low energy 6 MV filter, the 18 MV beam has a resultant larger field size S_h dependence than the 6 MV beam.

Measurements were also made to study the collimator-exchange effect. These results are shown in figures 4.9 and 4.10. What can be seen from the data is that the upper collimator jaws causes a larger field size dependence in S_h than the lower jaws. Similarly for the same size projected opening at 100 cm SAD, the lower jaw “allows” more scatter to reach the measurement point. These results can be considered in terms of the flattening filter mass model introduced above. Figure 6.3 a) and b) shows the change in visible mass of flattening filter for both the 6 MV and 18 MV beam where either the upper or lower jaws are fixed and the other jaws are allowed to vary. These results parallel the dosimetric observation in that when the lower jaws are fixed and the upper jaws are allowed to open the change in mass which is visible is the greatest.

Again, it is clear that the geometric first order mass model introduced here can qualitatively explain the empirical observation.

This work has also examined the changes in S_h as a function of off-axis distance (OAD). As can be seen from the measurement results reported in figures 4.11 and 4.12, the value of S_h for a given field size increases as a function of OAD. This increase in S_h is greater for smaller field sizes and becomes negligible for field sizes greater than 12 x 12 cm².

The OAD dependence of S_h was investigated in terms of the flattening filter visible mass model discussed above. The total flattening filter mass visible to an observer on the central axis and at 12 cm off-axis is compared in figure 6.4 a) and 6.4 b) for both 6 and 18 MV beams. As can be seen, the mass visible to an observer on the central axis is different than from 12cm off-axis. The total change in mass visible at 12 cm off-axis is less than the total change in mass seen on the central axis. This is consistent with the measured S_h data.

In conclusion, observation of how S_h changes with energy, the introduction of the flattening filter, collimator-exchange and OAD have been made. A model has been introduced which qualitatively describes the functional dependence of S_h in terms of the total mass of flattening filter visible to the observer at the measurement point.

Figure 6.1 Illustration of Flattening Filter Shape for the 6 MV and the 18 MV Photon Beams

Figure 6.2 Mass Change with Field Size for a Central Axis Point of Observation.

Figure 6.3 Flattening Filter Mass Change with Rectangular Fields
Change of flattening filter mass with size of variable rectangle side as seen from the isocenter for 6 MV (a) and 18 MV (b) beam.

Figure 6.4 Effects of Off-Axis Distance on Flattening Filter Mass Change
 Change of flattening filter mass with field size as seen from the field center at a 0 and a 12 cm off-axis distance [OAD] for 6 MV (a) and 18 MV (b) beam.

6.4 Monte Carlo Simulations

As part of this work, a detailed simulation of the Siemens KD2 linac head in 6 MV mode was performed to investigate the sources of head scatter which contribute to the measured S_h . The head components which were considered in these simulations included the flattening filter, the electron beam stopper, primary collimator, the photon monitor chamber and the secondary collimators. The various components were added serially to examine their individual effects on head scatter.

The overall increase in total head scatter as a function of the successive addition of head components is shown in figure 4.24 b) for on- and off-axis positions. As can be seen (and would be expected), the addition of head components in the beam path result in a larger portion of scored photons to be from scatter. The results are summarized in table 6.2 as a function of the off-axis angle or the radial distance from the center. The data are presented as fraction of the corresponding total photon fluence in the scoring region. This fraction represents the net increase in scatter due to each component. Table 6.2 also lists in brackets the mean energy of the scattered photons obtained from figure 4.25 b).

In the absence of the secondary collimator and at the beam center the total scatter is about 10 % of the total photon fluence decreasing slightly with off-axis distances (see table 6.2).

The combined scatter from the target, the window and air is important and increases with off-axis distance. Although not modeled in this work, it is assumed that the majority of this scatter observed with air alone comes from the high Z bremsstrahlung target where

most of the photons are produced. This was verified by Monte Carlo calculations performed by Chaney et al²¹ on a Siemens MD2 linac where they found that air scattered about 0.1 % of the total photons scored at 100 cm SAD.

What is interesting is the angular dependence of the scatter fluence when air alone is present in the simulation. In this case there is significantly more scatter at the beam periphery than on the central axis. This is due to the fact that scattered photons produced in the target are of smaller energy and are emitted at wider angle with respect to the normal than the unscattered photons.

As individual head components are added, the relative contribution of scatter photons increases. The introduction of the primary collimator causes approximately a 1.5% increase in scattered photons. This increase is relatively uniform across the entire clinically useful beam. Similarly the introduction of the electron beam stopper introduces a further 2% scatter, uniformly over the clinically useful beam area.

When the flattening filter is added an additional 5% scatter is scored on the central axis, but this is not uniform. The additional scatter introduced by the flattening filter is only approximately 1.5% at the beam periphery. Finally, when the mirror and monitor chambers are added into the simulation, they add approximately 1% to the total scatter over the full beam area to bring the total scatter to about 10% of all photons reaching the scoring plane. These results are summarized in table 6.2.

These results are somewhat misleading, in that each time a successive downstream component is added to the simulation it acts as an absorber to photons (primary and

scatter) produced upstream. Thus the data represents the net increase in scatter and not the relative contribution of one individual component.

The net influences of individual components are examined by removing them individually from the simulation when all other head components were left in place. This is shown in figure 4.26 when first the primary collimator was removed, then only the beam stopper was removed and finally when both the beam stopper and primary collimator were removed.

These results are somewhat surprising at first, in that they indicate that with the beam stopper in place, the removal of the primary definer resulted in more scatter to be scored across the entire useful beam. Examination of figure 3.1, which is a detailed blow up of the head construction, reveals the reason for this behavior. As can be seen, part of the beam stopper is geometrically obscured (relative to the clinically useful beam area at 100 SSD) by the primary collimator. Thus, when the primary collimator is removed, photon scatter in the obscured part of the beam stopper can reach the scoring region.

This work has also investigated the role of the secondary collimators and their geometric positions. Results of the Monte Carlo simulation are shown in figures 4.28 and 4.29. It can be seen from an examination of the data; that the amount of scatter reaching the scoring plane, for a given field size is a strong function of the distance from the secondary collimators to the source.

These results indicate that when all the jaws are placed at the level normally occupied by the upper jaws, the scatter varied from 4 to 10.3% of the total photon fluence for fields

of 4×4 and $26.5 \times 26.5 \text{ cm}^2$ respectively. In their Monte Carlo simulation on a similar Siemens treatment head, Chaney et al²¹ placed the combined thickness of the secondary collimators (i.e. the lower and the upper jaws) at the level of the lower jaws.

Comparable with the above results, they found a scatter range of 3% to 9% of the total photons at the central axis for a $4 \times 4 \text{ cm}^2$ to a $28.6 \times 28.6 \text{ cm}^2$.

When all secondary collimators were moved to the level of the lower jaws, the percentage of photons due to scatter changed to 5.8% ($4 \times 4 \text{ cm}^2$) and 10.5% ($26.5 \times 26.5 \text{ cm}^2$). This is consistent with our experimental results in which the same collimator-exchange effect was observed, and is likely a result of the collimator obscuring part of secondary scatter radiation source. This is discussed further at the end of this section.

The effect of the secondary collimator has also been studied in terms of its contribution to the on- and off-axis scatter. This is shown in figure 4.27. The curve labeled “open” refers to the case where the secondary collimators are removed completely from the model. What can be seen is that when the collimator jaws are set to maximum field size, they have virtually no effect on the photon fluence within the clinically useful portion of the beam. As the jaws are closed to a $26.5 \times 26.5 \text{ cm}^2$ field, they provide an increased fluence in terms of scatter, but as they are closed further to small field size they reduce the total scatter fluence. Thus, there is a competing field size dependent process associated with the secondary collimator. The collimators can act as a scatter source, as evidenced by the increase in scatter as they are closed from very large to medium size fields. However, as discussed in the previous section, they also act as an attenuator for

scatter radiation produced upstream. This is demonstrated by the reduction in scatter when either the collimator is not included or the jaws are closed to a $4 \times 4 \text{ cm}^2$ field. Our calculations indicate that for a medium size field the collimator can contribute up to 0.5% of the photon fluence. This is consistent with the results of Mohan et al⁴⁵ who found for a 15 MV beam from a Varian linac 0.2 % of the photons were scattered by the secondary collimator. The field size was not specified.

Our simulations, shown in figure 4.23 b, confirms the accepted notion that due to the nature of the bremsstrahlung production and to the shape of the flattening filter, the energy spectrum in the central part of the beam is harder than at points on the periphery of the beam. In the presence of all head components, with the exception of the secondary collimator, the mean energy of all photons on the beam axis was 1.87 MeV decreasing to 1.45 MeV in the scoring region at 9.6° off-axis angle (i.e. between 14 to 16 cm radial distance from center). This variation in mean energy with off-axis distance is consistent with the results by Mohan et al⁴⁵ who found for a 6 MV beam from a Varian linac the mean energy to vary from 1.92 to 1.51 MeV at the center and at radial distance between 15-20 cm from the center respectively. The scattered photon mean energy also displayed similar off-axis dependence in the presence of all head components (see table 6.2).

Figure 4.29 displays the behavior of the primary-to scatter ratios of fluence and energy fluence as a function of field size. The ratio decreases asymptotically with increasing field size reaching a plateau at large fields. For a field size of $15 \times 15 \text{ cm}^2$ the P/S ratio of fluence and energy fluence was estimated to be 10 ± 0.5 and 13.0 ± 0.5 respectively. In the model developed in this work to estimate head scatter factors, the P/S ratio for $15 \times 15 \text{ cm}^2$ field was used as a fitting parameter. The best P/S value at the central axis for the 6 MV beam was found to be 12.5, see figure 5.9, which is close to the Monte Carlo determined energy fluence ratio (i.e. 13). Dunscombe et al⁶ who used a Gaussian model to estimate head scatter factors, arrive at a ratio of 11.5 for unattenuated primary to scatter ratio for a $20 \times 20 \text{ cm}^2$ field for a 6 MV beam from Siemens KD2. Zhu et al³⁸ supplemented the results of the latter authors by showing a Gaussian model predicted P/S to fit well with experimentally determined values. They estimated a value of 0.072 (P/S =13.88) for a $20 \times 20 \text{ cm}^2$ field size from a Phillips SL25 linac. They also demonstrated that S/P ratios are very dependent on the linac head design.

Head scatter factors, shown in figure 4.30, were determined from Monte Carlo simulations which modeled the geometry and the polystyrene miniphantom used for measurement. The results suggested that S_h defined as the ratio of total (scatter + primary) energy fluence produces better agreement (to within 1%) with measured data than the ratio of total fluences alone. This indicates that the Monte Carlo simulations are consistent with the measured quantities and prescribing the head scatter factor as a ratio of the energy fluence is a better reflection of the photon scattering and energy changes

with field size. Note the simulated position of the secondary collimators was at the level of the upper jaws and as such the scatter reaching the central axis is underestimated. This effect is field size dependent and it is more important for small fields (see figure 4.28 a).

If on the other hand the secondary collimator was at the level of the lower jaws an increase in scatter for the same field dimension at SAD will result. For field sizes smaller than $10 \times 10 \text{ cm}^2$ the S_h values will increase and for field sizes greater than $10 \times 10 \text{ cm}^2$ will decrease. This will produce greater deviations between the Monte Carlo and measured results.

6.5 Asymmetric Fields Head Scatter Factor Model

The determination of relative output factors using non-traditional methods is currently an area of active research interest. The literature sites several new approaches^{6,66,67,68,69} for obtaining output factors; one of these involving the use of a two component (primary and scatter) x-ray source model to estimate head scatter factors^{6,67}.

Early work using the aforementioned approach has, in general, been encouraging. However, the evaluation of these head scatter factors invariably required numerical methods for solution. More recently, an x-ray source model, proposed by Yu and Sloboda, has afforded an analytic method for determining head scatter factors under certain provisos mentioned in the previous chapter.

Table 6.2 6 MV Head Component Scatter

Scatter as a fraction of total photon fluence for the various head components at 100 cm SAD. The head components were added successively between the target and the scoring regions (see section 4.12). The data represent the net increase due to each component.

The bracketed value is the scatter photon fluence weighted mean energy in MeV.

Maximum standard deviation in the data was less than 1.3 % of the tabulated value.

Off-Axis Angle (degrees)	Radial Distance (cm)	(a)	(b)	(c)	(d)	(e)	Total Photon Scatter
0	0-2	0.020 (0.67)	0.015 (0.98)	0.019 (0.91)	0.038 (1.28)	0.008 (1.26)	0.1 (1.26)
4	6-8	0.020 (0.67)	0.014 (0.95)	0.019 (0.88)	0.033 (1.23)	0.008 (1.24)	0.094 (1.24)
6.28	10-12	0.025 (0.65)	0.015 (0.95)	0.024 (0.89)	0.021 (1.12)	0.008 (1.17)	0.093 (1.17)
9.6	16-18	0.031 (0.63)	0.017 (0.91)	0.025 (0.86)	0.015 (1.02)	0.008 (1.05)	0.096 (1.05)

a) Air + target + window

b) Air + target + window + primary collimator

c) Air + target + window + primary collimator + electron beam stopper

d) Air + target + window + primary collimator + electron beam stopper + flattening filter

e) Air + target + window + primary collimator + electron beam stopper + flattening filter
+ mirror and monitor chamber

In chapter 5 the Yu and Sloboda model was extended to preclude any such provisos.

Head scatter factors were estimated for a large number of asymmetric fields for different energies both on-axis and off-axis. Although the geometries associated with the off-axis fields were somewhat more complicated, the calculation of these factors using this model was not insurmountable.

The model assumes that an x-ray source of a linac can be described as the sum of a primary and a scatter source component. The latter is associated with a radial function which defines the relative intensity distribution of the scatter at the base of the flattening filter. Although the function contains two positive-valued parameters, c and g , which may be varied to estimate the scatter contribution, c is essentially predetermined; it reflects the extent of the primary fluence at the base of the filter. In order to preserve this parameter's intended significance, c should not deviate dramatically from its apparent geometric value.

The results shown in the previous chapter disclose a maximum of 0.7% discrepancy between estimated head scatter factors and measured data for a c -value of 1.8 cm for asymmetric fields on axis and off-axis up to 12.0 cm. Interestingly, the c -value used is close to its expected value of 2.05 cm (Siemens KD2 Serial # 1784). Dunscombe et al³⁸ found the σ value of 1.01 cm in their Gaussian model to produce good estimates of head scatter factors on the central axis.

In the model, c should have a physical significance and is related to the extent of the primary photon fluence at the base of the field flattener. However, in the experimental

work and Monte Carlo simulations I have shown a complex nature to the scatter. Also it has been demonstrated that particularly at off-axis points, the influence of the flattening filter is diminished and other head components such as the electron beam stopper begins to play a larger role. Thus, the fact that varying the value of c off-axis (see figures 5.10 d and 5.11 d) gives a better result to the fit, does not necessarily diminish the significance of c , but points to its complex nature and the fact that at off-axis distance components at different locations (relatively geometry) in the head provide significant scatter.

The model which has been introduced is also strongly dependent upon the P/S ratio. For this model, the P/S ratio used is shown in figure 5.9. The Monte Carlo results, although for slightly different geometric conditions show a similar trend in P/S ratio over the OAD's relevant to this discussion as shown in figure 6.5. The results in this work are consistent with the work of Dunscombe et al⁷⁰ who extended their Gaussian model to estimate in-air relative output factor for on- and off-axis asymmetric fields. The P/S ratios found to fit their measured data ranged from 11.9 on-axis to 18.5 at 7.5 cm OAD. The reference field size was 20 x 20 cm².

Thus, I have introduced a model which provides accurate results for the prediction of S_h for asymmetric off-axis fields. The model requires 3 parameters, but for improved accuracy the parameters need to be adjusted at extended off-axis distances. This would indicate that the functional form of the scatter term f_{sca} is slightly different than given in equation 5.15 and further investigation of this is undoubtedly warranted.

Figure 6.5 Monte Carlo Primary-to-Scatter Ratio vs Off-Axis Angle

Primary to scatter ratio (P/S) vs angle from beam axis for a 7 MeV target electron beam. The P/S ratio was determined from Monte Carlo scored photon energy fluence. Scoring regions were in air. Error bars are $\pm \sigma$.

Chapter 7 Conclusions and Future Investigations

What I have shown in this work is that the scatter from the head of the Siemens linac is a complex function of the head components and their geometry. It has been demonstrated that on the central axis of the beam, the flattening filter plays the dominant role in defining the primary to scatter ratio. However, it has also been demonstrated that off axis, the role of the flattening filter is significantly reduced and the contribution of other head components such as the electron beam stopper and primary collimator become more important.

Further, it has been demonstrated that the role of the primary definer is to reduce the overall scatter incident at the scoring plane. The role of the mirror and ion chamber are relatively minor for the Siemens linac head.

The qualitative mass model, describing only the flattening filter, introduced in the discussion of the measured S_h values would appear much too simplistic. Ahnesjö²² developed closed form solutions to determine the amount of scatter reaching a calculation point from the visible part of the filter. This was done by considering the first-order Compton scatter released per unit filter area from a finite filter element. For the model to be significant it should be extended to include the mass of the major head components and their relative geometry.

As can be seen from the Monte Carlo simulation it is also important that a term be introduced to include absorption of photons (scatter and primary) produced upstream. Such a model, or extension of the work by Ahnesjö²² could form the basis of a solid

semi-empirical approach and could have clinical application for the rapid approximate determination of head scatter.

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Appendix A

S_{hsa} is the scatter contribution from the area in the secondary source plane that is observed on the central axis point, O_a , and illustrated in fig. 5.4. It can be expressed as:

$$S_{hsa} = \int_{R_{xy}} f_{soa}(x, y) dx dy \quad (A.1)$$

Substituting equation 5.17 for $f_{soa}(x, y)$ S_{hsa} can be written as:

$$S_{hsa} = \iint_{r \leq c} (1 - \frac{r}{c}) dx dy + \iint_{r \geq 0.0001} \frac{g}{r} dx dy \quad (A.2)$$

The first term in equation A.2 can be expanded to:

$$\iint_{r \leq c} (1 - \frac{r}{c}) dy dx = \overbrace{\int_{y_l}^{y_c} dy \int_{x1}^{\sqrt{c^2 - y^2}} dx}^{I1} - \overbrace{\int_{y_l}^{y_c} dy \int_{x1}^{\sqrt{c^2 - y^2}} \frac{r}{c} dx}^{I2} \quad (A.3)$$

Substituting a for $X1$ and integrating the term I1 with respect to dx will produce:

$$I1 = \int_{y_l}^{y_c} (\sqrt{c^2 - y^2} - a) dy \quad (A.4)$$

let $y = c \sin \theta \Rightarrow dy = c \cos \theta d\theta$. Then

$$\Rightarrow I1 = \left| \frac{c^2}{2} \sin^{-1} \left[\frac{y}{c} \right] + \frac{1}{2} y \sqrt{c^2 - y^2} - a \cdot y \right|_{y_l}^{y_c} \quad (A.5)$$

Substituting a for XI and $\sqrt{x^2 + y^2}$ for r in I2 of equation A.3, and

let $\tan \theta = \frac{y}{x} \Rightarrow dx = y \sec^2 \theta d\theta$. Then

$$\begin{aligned}
 I2 &= \frac{1}{c} \int_{y_i}^{y_u} y^2 dy \int_a^{\sqrt{c^2 - y^2}} \sec^3 \theta d\theta \\
 &= \frac{1}{c} \int_{y_i}^{y_u} y^2 dy \left\{ \sec \theta \tan \theta + \log \left[\sec \theta + \tan \theta \right] \right\}_a^{\sqrt{c^2 - y^2}} \\
 &= \frac{1}{2c} \int_{y_i}^{y_u} dy \left\{ x \sqrt{x^2 + y^2} + y^2 \right\}_a^{\sqrt{c^2 - y^2}} \\
 &= \frac{1}{2c} \int_{y_i}^{y_u} dy \sqrt{c^2 - y^2} \cdot c + \frac{1}{2c} \int_{y_i}^{y_u} dy y^2 \log \left[c + \sqrt{c^2 - y^2} \right] \\
 &\quad - \frac{1}{2c} \int_{y_i}^{y_u} dy \sqrt{a^2 - y^2} \cdot a - \frac{1}{2c} \int_{y_i}^{y_u} dy y^2 \log \left[a + \sqrt{a^2 + y^2} \right]
 \end{aligned} \tag{A.6}$$

term #1 in equation A.6 can be evaluated as equation A.4 to become:

$$\#1 = \left(\frac{c^2}{4} \sin^{-1} \left(\frac{y}{c} \right) + \frac{y}{4} \sqrt{c^2 - y^2} \right) \Big|_{y_i}^{y_u} \tag{A.7}$$

term #2 in equation A.6 can be integrated by parts with

$$u = \log\left[c + \sqrt{c^2 - y^2}\right], du = \frac{y dy}{\left[c + \sqrt{c^2 - y^2}\right]} \cdot \frac{1}{\sqrt{c^2 - y^2}} \cdot dv = y^2 dy \text{ and } v = \frac{y^3}{3}$$

and results in this expression

$$\#2 = \left(-\frac{y^3}{18c} - \frac{y\sqrt{c^2 - y^2}}{12} + \frac{c^2}{12} \sin^{-1}\left(\frac{y}{c}\right) + \frac{y^3 \log\left[c + \sqrt{c^2 - y^2}\right]}{6c} \right) \Bigg|_{r_l}^{r_t} \quad (\text{A.8})$$

term #3 in equation A.6 can be evaluated by substituting $\tan\theta = y/a$ and

$dy = a \sec^2 \theta d\theta$ and this will result in this expression

$$\#3 = \left(\frac{ay\sqrt{a^2 + y^2}}{4c} + \frac{a^3}{4c} \sinh^{-1}\left[\frac{y}{a}\right] \right) \Bigg|_{r_l}^{r_t} \quad (\text{A.9})$$

term #4 can be evaluated as #2 term resulting in this expression

$$\#4 = \left(-\frac{y^3}{18c} - \frac{a^3 \sinh^{-1}\left[\frac{y}{a}\right]}{12c} - \frac{y^3 \log\left[a + \sqrt{a^2 + y^2}\right]}{6c} + \frac{ay\sqrt{a^2 + y^2}}{12c} \right) \Bigg|_{r_l}^{r_t} \quad (\text{A.10})$$

I2 in equation A.3 is given by equation A.7+ equation A.8 - equation A9 - equation A10.

$$\Rightarrow I2 = \frac{1}{6} \left[\begin{aligned} & y\sqrt{c^2 - y^2} - \frac{2ay\sqrt{a^2 + y^2}}{c} + 2c^2 \sin^{-1}\left[\frac{y}{c}\right] - \frac{a^3 \sinh^{-1}\left[\frac{y}{a}\right]}{c} \\ & + \frac{y^3 \log\left[c + \sqrt{c^2 - y^2}\right]}{c} - \frac{y^3 \log\left[a + \sqrt{a^2 + y^2}\right]}{c} \end{aligned} \right] \Bigg|_{r_l}^{r_t} \quad (\text{A.11})$$

Thus the solution of equation A.3 is given by equation A.5 - equation A.11

$$\iint_{r \leq c} \left(1 - \frac{r}{c}\right) dy dx = \frac{l}{6c} \left[\begin{aligned} &-6acy + 2cy\sqrt{c^2 - y^2} + 2ay\sqrt{a^2 + y^2} + c^3 \sinh^{-1}\left[\frac{y}{c}\right] \\ &+ a^3 \sinh^{-1}\left[\frac{y}{a}\right] - y^3 \log\left[c + \sqrt{c^2 - y^2}\right] \\ &+ y^3 \log\left[a + \sqrt{a^2 + y^2}\right] \end{aligned} \right] \Bigg|_{Y_L}^{Y_U} \quad (\text{A.12})$$

The second integral in equation A.2 can be expressed as:

$$\begin{aligned} \iint_{r \rightarrow 0.0001}^r \frac{g}{r} dy dx &= \int_{Y_L}^{Y_U} dy \int_{X1}^{X2} \frac{g}{\sqrt{x^2 + y^2}} dx \\ &= \left[\begin{aligned} &-g \cdot y \log\left[a + \sqrt{a^2 + y^2}\right] - a \cdot g \log\left[y + \sqrt{a^2 + y^2}\right] + \\ &g \cdot y \log\left[X_{soa} + \sqrt{X_{soa}^2 + y^2}\right] + g \cdot X_{soa} \log\left[y + \sqrt{X_{soa}^2 + y^2}\right] \end{aligned} \right] \Bigg|_{Y_L}^{Y_U} \quad (\text{A.13}) \end{aligned}$$

where the limits of integration are given by:

$$\begin{aligned} Y_L &= -\sqrt{c^2 - a^2} \\ Y_U &= \sqrt{c^2 - a^2} \\ X1 &= a \\ X2 &= a + \frac{k_x \cdot X_{oa}}{2} \end{aligned}$$

Appendix B

The mass of flattening filter, $m_{x,y}$, observed from a field center located in the isocenter plane is given by:

$$m_{x,y} = \rho \int_{y2}^{y1} dy \int_{x1}^{x2} dx f(x, y) \quad (B1.1)$$

where $f(x, y)$ is a two dimensional function defining the flattening filter height(profile) from its base and ρ is the density of the filter material. The flattening filter area visible from the field center can be determined in a similar way as described in section 5.3.1. This area is delineated by the projections into the filter base plane of the upper and lower collimator offsets from the field central ray (see figures 5.4 and 5.5).

The derived function, $f(x, y)$, that best fit the 6 MV flattening filter profile is given by:

$$f(x, y) = -7.2 + 30.7 \exp\left(-\frac{\sqrt{x^2 + y^2}}{14.6}\right) \quad (\text{mm}) \quad (B1.2)$$

Similarly $f(x, y)$ for the 18 MV flattening filter is given by:

$$f(x, y) = -0.59 + 59.8 \exp\left(-\frac{\sqrt{x^2 + y^2}}{6.3}\right) \quad (\text{mm}) \quad (B1.3)$$

Figure B1.1 shows a comparison between the measured and the fitted flattening filter profile for the 6 and 18 MV beams.

The limit of integration in equ. B1.1 are given by:

$$X1 = \left(\sigma a_r \frac{d}{SAD} \right) - \frac{k_r X}{2} \quad (B1.4)$$

$$X2 = (oa_x \frac{d}{SAD}) + \frac{k_x X}{2} \quad (B1.5)$$

$$Y1 = (oa_y \frac{d}{SAD}) - \frac{k_y Y}{2} \quad (B1.6)$$

$$Y2 = (oa_y \frac{d}{SAD}) + \frac{k_y Y}{2} \quad (B1.7)$$

where X and Y are the field dimensions at SAD and the rest of the parameters are defined in section 5.3.1.

Equation B1.1 was evaluated numerically using the program Mathematica⁷¹.

Figure B1.1 Measured and Fitted Flattening Filter Profile
 Comparison between measured and fitted flattening filter profile for 6 MV (a) and 18 MV (b) from Siemens KD2 linac.

IMAGE EVALUATION TEST TARGET (QA-3)

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