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**What constitutes a clinic-like
radiotherapy photon beam**

by

Nina Kalach

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

Master of Science

Department of Physics
Carleton University
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Ottawa, Canada
July 22, 2001

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“What constitutes a clinic-like
radiotherapy photon beam”

submitted by Nina Kalach
in partial fulfillment of the requirements
for the degree of Master of Science

Chair, Department of Physics

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Abstract

Using an extensive set of calculated and measured bremsstrahlung photon spectra from a variety of linear accelerators, the relationship is studied between beam quality specifiers used in clinical practice and water to air stopping-power ratios, $\left(\frac{L}{\rho}\right)_{air}^w$.

Based on the Monte Carlo calculations for 12 sets of bremsstrahlung photon spectra, it is shown that $\%dd(10)_x$, the photon component of percentage depth dose at 10 cm for a 10 x 10 cm² field at an SSD of 100 cm, is a unique beam quality specifier for all photon beams studied. This confirms previously reported results but for a broader range of beams.

It is shown that for all of the 14 standard clinical beams studied, including detailed models of Varian, Siemens and Elekta machines, TPR_{10}^{20} , the Tissue-Phantom Ratio at 20 and 10 cm depths in a water phantom, is an adequate beam quality specifier, but it is not a good beam quality specifier for the MM50 beams nor many other beams in standards laboratories.

It was found that, with caution, TPR_{10}^{20} can be used as a beam quality specifier for clinical and “clinic-like” spectra. The numerical relationship, derived in the present work between TPR_{10}^{20} and $\%dd(10)_x$ for all “clinic-like” spectra gives an easily used criterion for establishing if a given beam is clinic-like or not, i.e. for establishing if TPR_{10}^{20} is a good beam quality specifier or not.

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Notation and Conventions

TPR₁₀²⁰ - Tissue-Phantom Ratio at 20 and 10 cm depths in a water phantom or the ratio of the ionization or absorbed doses at the depths of 20 and 10 cm for a field size of 10 x 10 cm² defined at constant source-detector distance (SDD).

%dd(10)_x - *photon component* of the percentage depth dose at 10 cm for a 10 x 10 cm² field defined for a distance between the source and the water phantom surface (SSD) of 100 cm.

%dd(10) - percentage depth dose at 10 cm for a 10 x 10 cm² field defined for a source-surface distance (SSD) of 100 cm.

$\left(\frac{\bar{L}}{\rho}\right)_{\text{air}}^{\text{w}}$ - the ratio of the electron spectrum averaged restricted mass collision stopping powers for water to air.

NAP in MV - Nominal Accelerating Potential reported in MV (megavolts), which is related to the energy in MeV of the electrons produced by accelerator and the target/filter system.

HVL₁ - first half-value layer is defined as the thickness required to reduce the exposure by half, in narrow-beam geometry.

HVL₂ - second half-value layer is the thickness necessary to reduce the exposure by half after it has being reduced by HVL₁, in narrow-beam geometry.

Particle fluence Φ , m⁻² is defined by the ICRU as the quotient of dN by da , where dN is the number of particles incident on a *sphere* of cross-sectional area da

$$\Phi = \frac{dN}{da} \quad (1)$$

It should be distinguished from planar photon fluence which decreases when the beam is not at normal incidence whereas particle fluence remains the same in both cases.

An alternative definition of particle fluence is that it is equal to the sum of the particle track length in a volume, divided by the volume. The equivalence to the ICRU definition has been formally proved by Chilton.^{1,2}

Planar photon fluence - the number of particles crossing a plane per unit area.

Relative photon fluence - planar photon fluence of the photons normalized to unity at the maximum of the spectrum.

Relative energy fluence - relative photon fluence multiplied by the energy at the center of each bin and normalized to unity at the maximum of the spectrum.

Relative kerma fluence - relative energy fluence multiplied by the mass-energy absorption coefficient $\frac{\mu_{en}}{\rho}$ for water normalized to unity at the maximum of the spectrum. The mass-energy absorption coefficient for water is taken from the work of Hubbell and Seltzer³ and linearly interpolated for the energy at the center of each bin.

Chapter 1

Introduction

1.1 General introduction

Megavoltage photon beams were introduced clinically in the 1950s to treat deep-seated tumours due to their high penetrating characteristics. In medical linear accelerators (linacs), the high energy photon beam is produced when a narrow monoenergetic beam of accelerated electrons impinges on a high Z material target (copper and tungsten are the common choices) producing a bremsstrahlung photon beam. The photon beam is forward peaked in a bullet-shaped lobe and is further collimated by a beam collimating system which includes a fixed primary collimator, a set of adjustable jaws, multileaf collimators and blocks. To create a uniform beam over the clinically useful field sizes at the surface of the patient (or water phantom), a flattening filter is used, which is usually shaped like a cone with the apex facing the target. The flattening filter is made of tungsten or steel or a lead/steel combination. Any material between the target and the patient (water phantom) surface affects the spectral distribution of the radiation beam reaching the surface, contributing the scattered photons and

secondary electrons. Those secondary electrons are referred to as electron “contamination”.

The purpose of the radiation dosimetry in radiotherapy is to predict the doses to the tumour and normal tissues of the patient undergoing radiotherapy. It is done in two steps: first, absorbed dose to the water delivered by the accelerator beam incident on a phantom is measured using ion chamber under a specified set of reference conditions^{4,5} and then one uses the reference dose data and the patient data (CT image of the tumour, etc.) to predict the dose at any point in the patient by means of mathematical algorithms.⁶⁻⁸

The outcome of a radiotherapy treatment depends on the accuracy of the dose delivery. It has been shown that an underdosage of 5% in the dose delivered to the tumour can decrease the tumour probability control by more than 15% while a 5% increase in the dose delivered to the tumour can cause intolerable side effects in the surrounding healthy tissues.^{9,10} The design of the biologically optimal treatment schedule is achieved by assessment of the delivered dose distribution and by establishment of the biologically relevant quantities such as tumour control probabilities, biologically effective doses, normal tissue complication probabilities. All this requires that systematic uncertainties in dosimetry be made as small as reasonable compared to the uncertainties in defining the target volume (tumour outline, patient geometry, tissue inhomogeneities, patient movement) and tumour response (clinical outcome, cell survival fractions).^{4,7} With a recent absolute dosimetry uncertainty estimate of 2%,¹¹ 1% accuracy in reference dosimetry was referred to as an ultimate future goal.⁸

The new AAPM TG-51 dosimetry protocol⁵ defines the dose to the water at the point of measurement of the ion chamber in the absence of the chamber for a

beam of quality Q as

$$D_w^Q = Mk_Q N_{D,w}^{60Co} \quad (1.1)$$

where D_w^Q is the absorbed dose to the water (Gy), M is the fully corrected electrometer reading (coulombs or meter units), k_Q is a beam quality conversion factor and $N_{D,w}^{60Co}$ is the absorbed dose to the water calibration factor for the ion chamber placed under reference conditions in a ^{60}Co beam and it is traceable to the Primary Standards Laboratory.

Spencer-Attix cavity theory¹² relates the dose delivered to the gas in an ion chamber, D_{gas} , to the dose in the surrounding medium, D_{med} by the relationship:

$$D_{med} = D_{gas} \left(\frac{\bar{L}}{\rho} \right)_{gas}^{med} \quad (1.2)$$

where the stopping-power ratio, $\left(\frac{\bar{L}}{\rho} \right)_{gas}^{med}$, is the ratio of the spectrum averaged restricted mass collision stopping powers for the medium to that for the gas where averaging extends from a minimum energy Δ to the maximum electron energy in the spectrum.¹³

$$\left(\frac{\bar{L}}{\rho} \right)_{gas}^{med} = \frac{\int_{\Delta}^{E_{max}} \Phi_T \left(\frac{L(\Delta)}{\rho} \right)_{med} + TE_{med}}{\int_{\Delta}^{E_{max}} \Phi_T \left(\frac{L(\Delta)}{\rho} \right)_{gas} + TE_{gas}} \quad (1.3)$$

The restricted stopping power $\left(\frac{L(\Delta)}{\rho} \right)$ includes only energy exchanges less than Δ and TE is a term to account for the dose from electrons whose energy falls below Δ .

The beam quality conversion factor k_Q is defined as

$$k_Q = \frac{N_{D,w}^Q}{N_{D,w}^{60Co}} \quad (1.4)$$

where $N_{D,w}^Q$ is an ion chamber calibration factor in a beam of quality Q and $N_{D,w}^{60Co}$ is the chamber calibration factor in the ^{60}Co beam as above. The beam quality conversion factor is, in principle, a measurable quantity and it is chamber dependent.

When calculated theoretically¹² k_Q is

$$k_Q = \frac{\left[\left(\frac{\bar{L}}{\rho}\right)_{air}^w P_{wall} P_{fl} P_{gr} P_{cel}\right]_Q}{\left[\left(\frac{\bar{L}}{\rho}\right)_{air}^w P_{wall} P_{fl} P_{gr} P_{cel}\right]_{^{60}Co}} \quad (1.5)$$

where $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$ is the ratio of the spectrum averaged restricted stopping powers for water to air, the P_i are chamber correction factors which depend on the beam quality, evaluated for the beam of quality Q and the ^{60}Co beam. Energy deposited in the air per coulomb of charge released, $\left(\frac{W}{e}\right)_{air}$, has been assumed constant.

Fig. 1.1 shows the energy dependence of k_Q and its components as in Eq. 1.5 for the NE2571 Farmer-like ion chamber (the range of changes was typical for all cylindrical Farmer-like ion chambers studied). It can be seen from Fig.1.1 that the variation in the stopping-power ratio $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$ dominates the photon beam quality dependence of the k_Q factor, decreasing from the 1.13 for ^{60}Co beams to 1.05 for a 50 MV bremsstrahlung beam which has a $\%dd(10)_x$ value of 95%, (see also Fig. 3.2).

1.2 History of beam quality specifiers

The x-ray beam “quality” usually refers to its “hardness”, i.e. penetrating ability. In the earlier days of radiotherapy, before megavoltage beams became generally available, the effectiveness of x-ray treatment of deep-seated tumours depended on the ability of the orthovoltage x-ray to penetrate to the tumour while limiting the dose to the surrounding tissue. For this reason, the more penetrating is the beam, the better its quality. “Quality” of radiation is also used in a more general sense to mean the spectral energy distribution of the photons.¹⁴

The quality of the photon beam could be specified in terms of its energy spectrum or its attenuation characteristics in the reference medium. To characterize

Figure 1.1: Beam quality conversion factor k_Q and energy dependent correction factors as a function of beam quality for the NE2571 Farmer-like ion chamber with 0.065 g/cm^2 graphite walls, inner diameter of 6.3 mm and an aluminum electrode with 1 mm diameter, calculated by Rogers.¹² Values of $(\text{spr})_{60\text{Co}}^Q$ and $(P_i)_{60\text{Co}}^Q$ are the quotients, as used in Equation 1.5, of water to air stopping-power ratios, $\left[\left(\frac{L}{\rho}\right)_{\text{air}}^w\right]_Q / \left[\left(\frac{L}{\rho}\right)_{\text{air}}^w\right]_{60\text{Co}}$, and the chamber correction factors, $[P_i]_Q / [P_i]_{60\text{Co}}$, evaluated for a beam of quality Q and a ^{60}Co beam.

orthovoltage ($\leq 300 \text{ kV}$) x-ray beams, several quantities have been employed, such as first and second half-value layers, HVL_1 and HVL_2 for either aluminum ($\leq 120 \text{ kV}$) or copper ($\leq 0.5 \text{ MV}$) or equivalent photon energy $h\nu_{eq}$ together with applied voltage V_{ap} . The beam quality specifiers for an orthovoltage x-ray beam rely on the fact that the photoelectric effect is the dominating interaction by photons below a few hundred keV and the photoelectric interaction coefficient varies approximately as $(1/h\nu)^3$ in this energy range. Therefore the energy spectrum of the x-ray beam in narrow beam geometry is “hardened” by adding layers of Al or Cu since low-energy photons are progressively filtered out of the beam and the spectral distributions becomes narrower approaching the energy of the applied voltage V_{ap} . Then, HVL_1 and HVL_2 (or homogeneity coefficient $\text{HVL}_1/\text{HVL}_2$) provide information about the

“hardness” (or average energy of the beam) and breadth of the spectrum. Similarly, equivalent photon energy $h\nu_{eq}$, defined as the energy of a monoenergetic beam having the same HVL_1 as the beam of interest, together with applied voltage, V_{ap} , conveys information on the spectral width which is roughly $2(V_{ap} - h\nu_{eq})$ for heavily filtered orthovoltage beams.¹⁴

For megavoltage photon beams, unique characterization by means of half-value layers in pure metals is not possible since the Compton effect becomes the dominating interaction process, which makes HVL a slowly varying function of energy. Pair production also becomes more important at higher energies tending to filter out the highest energy photons through pair production which may mean that HVL starts to decrease with “better” beam quality.¹⁵ Specification of a high energy photon spectrum is the most precise way of beam characterization, keeping also in mind that the spectrum may not be uniform over the beam area. The hardness of the megavoltage photon beam also can be characterized using the curves of absorbed dose vs. depth in a water phantom, measured under reference conditions.

For years, megavoltage photon beam quality has been characterized by the nominal accelerating potential (NAP in MV) which is related to the energy in MeV of the electrons produced by the accelerator. This energy is not always well known and, more importantly, the beam quality is affected by the thickness and material of the flattening filter and the target. This led to assigning the same quality for beams which produced substantially different depth-dose curves in water. The Nordic dosimetry protocol (NACP) was the first to introduce measured ratios of ionization or dose at two depths in a water phantom $I(10)/I(20)$ for a $10 \times 10 \text{ cm}^2$ field size at the surface and constant source-to-surface distance (SSD) to specify generic nominal accelerator potential,¹⁶ which then was used for the selection of the appropriate conversion fac-

tors. The American Association of Physicists in Medicine (AAPM) protocol TG-21⁴ went further and associated the beam quality with stopping-power ratios needed in the dose equation of the protocol, based on the work of Cunningham and Schulz.¹⁷

Since then, several measurable quantities have been proposed to choose appropriate stopping-power ratios such as the depth in water of the maximum dose d_{max} ,¹⁸ depth in water where the dose reaches 80% of the maximum dose d_{80} ,¹⁵ HVL in water measured in the “narrow beam” geometry,¹⁹ the moments of the spectral distribution which can be derived from the measurements of primary kerma in a mini-water-phantom in narrow-beam geometry,²⁰ forward dose perturbation factor, FDPF,²¹ Tissue-Phantom Ratio at 20 and 10 cm depths in the water phantom TPR_{10}^{20} , photon component of the percentage depth dose at 10 cm $\%dd(10)_x$ for the 10 x 10 cm² field at SSD of 100 cm, etc. The present work concentrates on the last two quantities since they are the two most widely used in clinical practice as beam quality specifiers.

Many existing dosimetry protocols^{4,22,23} use TPR_{10}^{20} as a beam quality specifier (which coincides with the definition of Tissue-Phantom Ratio routinely used in isocentric treatment planning calculations). TPR_{10}^{20} is the ratio of the ionization or absorbed doses at depths of 20 and 10 cm for a 10 x 10 cm² field size defined at a constant source-to-detector distance (SDD). Linac manufacturers are still using NAP and percentage depth-dose at 10 cm to specify an accelerator. Although better than NAP, TPR_{10}^{20} has been shown to select appropriate stopping-power ratios only to within an accuracy of 1.4% for bremsstrahlung spectra with the same TPR_{10}^{20} when extreme spectra (thin target spectra and thick target clinical spectra) are considered.²⁴ Using Monte Carlo calculations, Konsunen and Rogers²⁵ have shown that TPR_{10}^{20} is not a unique beam quality specifier for thick target beams, giving a 0.7% difference between

stopping-power ratios of calibration spectra at NRC and an available set of clinical spectra. They also showed that racetrack microtron accelerators have different curves of stopping-power ratios vs. TPR_{10}^{20} than other clinical machines. It has also been pointed out that TPR_{10}^{20} is an insensitive quality specifier for higher energy beams.²⁵

LaRiviere¹⁸ proposed that beam quality in MV should be related to $\%dd(10)$, the percentage depth-dose at 10 cm depth in a 10 x 10 cm² field at SSD of 100 cm. Using a combination of calculations based on published spectra and experimental depth-dose curves, he also showed an excellent correspondence between $\%dd(10)$ and the dose-weighted mean energy of the photon beams $\bar{E}_d$, MeV. Following this, Konsunen and Rogers²⁵ have done an extensive series of Monte Carlo calculations for published clinical spectra²⁶ and other realistic bremsstrahlung spectra. They have shown that $\bar{E}_d$ strongly correlates with stopping-power ratios and found a tight linear relationship between calculated values of $\%dd(10)$ and stopping-power ratios. They also pointed out that the electron contamination at the depth of the maximum dose and possibly 10 cm was a potential drawback of the using $\%dd(10)$ as a unique beam quality specifier, but that this could be overcome. Rogers and Yang²⁷ updated a linear relationship between calculated values of $\%dd(10)$ and $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$ based on the $\%dd(10)$ calculated for point source beams. Johnsson et al²⁰ confirmed the unique relationship between $\%dd(10)$ and stopping-power ratios and their data are in tight agreement with results of Rogers and Yang.²⁷

Work by Li and Rogers²⁸ and Rogers²⁹ suggested a simple method of measuring the photon component of the percentage depth-dose at 10 cm, $\%dd(10)_x$, using thin lead foils. The new AAPM dosimetry protocol, TG-51,⁵ adopted $\%dd(10)_x$ as its photon beam quality specifier.

Ross et al³⁰ measured beam quality conversion factors for several ionization

chambers in different high energy beams. They showed that using TPR_{10}^{20} as a beam quality specifier can lead to errors of up to 1% in the k_Q assignment whereas total percentage depth dose at 10 cm, $\%dd(10)_x$, and forward dose perturbation factor, FDPF, uniquely specified k_Q for six beam qualities studied.

Using their extensive measurements and the available published data on measured k_Q factors for the NE2571 and NE2611A ion chamber types, Seuntjens et al³¹ showed that the spread in k_Q values vs. $\%dd(10)_x$ is only 0.4% and 0.6%, respectively, over the entire measurement range, compared to spreads of up to 1.1% for both chambers when the k_Q values are expressed as a function of TPR_{10}^{20} . They also found that using $\%dd(10)_x$ improves overall consistency of the measured data from a variety of accelerator beams for the six types of chamber due to the fact that $\%dd(10)_x$ properly specifies the soft (light filtration) NRC beams whereas TPR_{10}^{20} does not.

1.3 Concept of a “clinic-like” bremsstrahlung photon beam

It has been argued^{32,33} that TPR_{10}^{20} is an adequate beam quality specifier for clinical or “clinic-like” machines and that it only fails for non-clinical machines at standards labs. Originally Andreo and Brahme³⁴ showed a unique relationship between TPR_{10}^{20} and stopping-power ratios based on Monte Carlo calculations for a very few realistic clinical spectra. In order to increase the data set available for clinical dosimetry, those authors have introduced a set of bremsstrahlung spectra calculated for some combinations of tungsten targets and lead filter thicknesses considered by them as typical for clinical machines. They chose a single target thickness of $r_0/3$, where r_0

is the CSDA range in tungsten at the energy of electrons incident on the target, and additional lead filtration ranging in thickness from 1 to 6 cm for the energy range 2 - 50 MV. They obtained very tight agreement between the $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$ vs. TPR_{10}^{20} curves for Mohan and other published spectra and for the Pb filtered “clinic-like spectra” data sets.

Konsunen and Rogers²⁵ have noted that stopping-power ratios and TPR_{10}^{20} values for aluminum thick target spectra filtered by 14 cm of aluminum are very close to the “clinical spectra” curve and suggested that this confirms the approach of the National Physical Laboratory, UK (NPL) of using a thick aluminum filters to make their thick target spectra more “clinic-like”. At the same time Andreo argued³² that, since the targets and flattening filters used at NPL are much thicker than those used in clinical accelerators, they can not be considered equivalent to those used in clinical practice.

Andreo³³ suggested that “as in case of kilovoltage x-ray dosimetry, in which the use of HVL must be complemented with information on beam filtration and kV, TPR_{10}^{20} can be meaningless if the accelerator potential and the target and filter combinations used to derive stopping-power data are completely ignored”. He also pointed out that it is possible to have non-clinical beams at the standards laboratories which could be considered to be “clinic-like” in the sense that TPR_{10}^{20} can be an adequate beam quality specifier.

It has been suggested^{33,35} that some knowledge of the target and flattening filter materials and thicknesses might improve the accuracy of the assignment of stopping-power ratios using TPR_{10}^{20} as the beam quality specifier. The Monte Carlo simulations of the modern commercial accelerators by Sheikh-Bagheri³⁶ reveals the variety of the materials and thicknesses of targets and flattening filters employed

by linac manufacturers. The typical modern clinical accelerator target is made of tungsten on a copper base or gold or of pure copper, with thicknesses much thicker than 0.33 times the CSDA range at the relevant electron energies for those materials (for example, some typical combinations are $0.7r_0$ in tungsten and $0.3r_0$ in copper, $0.2r_0$ in tungsten and $0.7r_0$ in copper, $0.7r_0$ in copper, etc.). The typical flattening filters are made of a wide variety of materials, from aluminum to tungsten. They have very complicated shapes or combinations of shapes which are partially inserted in the primary collimator. Their thicknesses range from, approximately, 2 cm of Cu to the 12 cm combined thickness of Al and stainless steel where “thickness” is evaluated as the distance from the apex of a quasi-conical structure to its bottom. Those thicknesses are not directly comparable to the thicknesses of flat lead filtration used by Brahme and Andreo.³⁵ It is also known that some clinical accelerators, such as the racetrack microtron machines, do not have a flattening filter and use thin targets. Very often details of the accelerator head design are not very well known since they constitute proprietary information (which is a substantial problem for the Monte Carlo simulation of commercial radiotherapy treatment units^{36,37}).

As described above, the lack of a quantitative criterion for what constitutes a “clinic-like” photon beam is a serious shortcoming. The purpose of this work was to establish if TPR_{10}^{20} is a good beam quality specifier for all clinic-like beams and if it is, to establish a usable criterion by which a given accelerator beam can be deemed clinic-like in the sense that TPR_{10}^{20} accurately specifies the $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$ or k_Q factors for this beam.

1.4 Thesis Overview

Chapter 2 describes in detail the calculational methods and computer packages used in the present work, including the BEAM code system (section 2.1) and the DDSPR code (section 2.4.2) both based on the EGS4³⁸ code system and the FLURZnrc user-code based on the EGSnrc Monte Carlo system (section 2.5). Chapter 2 also summarises the different calculations done in this work and describes sources of data taken from elsewhere, for accelerator spectra and for various beam quality specifiers.

Chapter 3 presents calculated water to air stopping-power ratios, $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$, versus $\%dd(10)_x$ and TPR_{10}^{20} values for the 12 sets of photon beams studied. Section 3.1 shows that TPR_{10}^{20} is an adequate beam quality specifier for the 14 beams studied from clinical accelerators and “clinic-like” beams from standards laboratories accelerators, but it is not a good quality specifier for the MM50 beams nor many other beams in standards laboratories. Section 3.2 shows that $\%dd(10)_x$ is a unique beam quality specifier for all photon beams studied and gives a linear relationship between values of $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$ and $\%dd(10)_x$ obtained as a fit to the present work results.

Based on the beam quality specifier values calculated in the present work and 7 more sets of measured pairs of beam quality specifiers available from literature, Section 3.3 presents a relationship between TPR_{10}^{20} and $\%dd(10)_x$ for a family of clinical and “clinic-like” spectra. The numerical relationship between TPR_{10}^{20} and $\%dd(10)_x$ for all “clinic-like” spectra given in Section 3.3 establishes an easily used criterion whether a given beam is clinic-like or not, i.e. for establishing if TPR_{10}^{20} is a good beam quality specifier or not.

Chapter 2

Calculational Methods

2.1 BEAM Monte Carlo system.

Many of the calculations of either accelerator spectra or beam quality specifiers were done with the BEAM code system which includes the BEAM³⁹ and DOSXYZ⁴⁰ user-codes based on EGS4,³⁸ the BEAMDP⁴¹ data processing tool, and the Graphical User Interfaces (GUIs) for these three codes.⁴² The BEAM code has been designed to simulate the radiation beam from any radiotherapy source, including electron and photon beams from accelerators. The features of the BEAM system make it an excellent research tool which allows modelling of a wide variety of accelerators. In addition, it has a variety of variance reduction techniques implemented which can save significant quantities of computing time.

BEAM is based on the PRESTA extension of the EGS4 Monte Carlo system for simulating radiation transport. A basic element of the BEAM design is that the model is built up from a series of component modules (CMs), each of which

operates completely independently of the others. Each CM deals with a specific class of geometric shape but does not specify explicit values related to the geometry. Once the model is built it still can be used to simulate a wide variety of configurations since each simulation reads a user specified input file which can be created using a graphical user interface.

The BEAM code produces a phase-space file (i.e., the position, energy, direction, charge and history tag for each particle) at any specified plane in the model. This phase space file can be re-used by BEAM or analyzed using a data analysis program such as BEAMDP.⁴¹ To allow flexible access to the particle's history, BEAM includes a general technique built on the LATCH feature of EGS4. A LATCH variable is associated with each particle, it is passed to a particle's descendents and can be interrogated or modified by the user. In BEAM, each bit of LATCH is manipulated separately. The LATCH technique allows one to separate effects of particles which have entered a water phantom from those that have been produced from particle interactions in the phantom, etc.

To estimate statistical uncertainties of Monte Carlo results, BEAM follows a general method described by Rogers and Bielajew.⁴³ For all scored quantities, a statistical estimate of the uncertainty on the quantity of interest is given by breaking the calculation into an arbitrary number of separate runs (batches), each considering the same number of histories, and each quantity of interest, x_i , is estimated for each batch. With N_B such estimates, the final estimate of x is the average $\langle x \rangle$ of the x_i values. On the assumption that the x_i are drawn from a normal distribution and the law of large numbers tells us this is always the case for a sufficient number of

histories, an estimate of the true variance of the mean, σ^2 , is given by

$$s_{\langle x \rangle}^2 = \frac{1}{N_B(N_B - 1)} \sum_{i=1}^{N_B} (x_i - \langle x \rangle)^2 \quad (2.1)$$

For $N_B=10$ used by BEAM, it is assumed that the interval $(\langle x \rangle - s, \langle x \rangle + s)$ contains the true value of the mean in about 68% of all cases, or 95% of all cases for $\pm 2s$.

The BEAM code is written in MORTRAN3, a FORTRAN77 preprocessor which is used for the EGS4 system. The BEAM system runs under UNIX or Linux operating systems. A BEAM simulation can be split into smaller jobs which can be run on different processors in parallel to reduce elapsed time for a simulation. Once the parallel jobs are complete, their dose and fluence results can be recombined and analyzed. BEAM then sums the results for parallel jobs in each statistical batch and performs a statistical analysis on the result.

During almost all BEAM simulations, constant values $ECUT=0.7$ MeV and $PCUT=0.01$ MeV have been used so that electrons and photons were transported down to those energies (including rest mass), respectively. When the particle's energy reaches these values, its energy is deposited locally. To make calculations more efficient, BEAM's range rejection technique (with set ECUTRR) and selective bremsstrahlung splitting (SBS) have been used.⁴⁴ The basic method for range rejection is to calculate the range of a charged particle and terminate its history (depositing all of its energy at that point) if it can not leave the current region. For each medium in an accelerator, BEAM calculates a table of ranges to the electron transport cutoff energy (ECUT) as a function of electron energy. These ranges are calculated using restricted stopping powers and thus represent the longest possible ranges to the cutoff energy. When range rejection with set ECUTRR is chosen, range rejection is performed on a region by region basis. If the range to the cutoff energy (ECUTRR) is less than the distance to the nearest region boundary, the history is

terminated and energy is deposited in the current region. Range rejection introduces an approximation because, in terminating a charged particle's history and depositing all of its energy in the current region, it is assumed that any bremsstrahlung photons that would have been created by the particle, do not leave the current region. One can minimize inaccuracy resulting from this approximation by using the variable ESAVE which defines the maximum charged particle energy (in MeV) at which range rejection is considered. Electrons having an energy larger than ESAVE are not considered for range rejection since they may produce bremsstrahlung photons which might escape the region. Sheikh-Bagheri³⁶ evaluated that a value of ESAVE=2 MeV provides a three-fold increase in the speed of the calculations and ignores only 0.1% of the photons reaching scoring plane at an SSD of 100 cm. These ignored photons are bremsstrahlung photons produced in a linac geometry at energy below ESAVE. Electron range rejection was turned off during some simulations although it should have been used in all cases to improve calculation efficiency. When using selective bremsstrahlung splitting, the typical minimum and maximum number of bremsstrahlung photons $N_{min}=10$, $N_{max}=250$ with a field size of 20x20 cm² at 100 cm SSD was used in almost all simulations, except where it is explicitly stated otherwise.

2.2 Overview of the calculations

The present calculation of the stopping-power ratios, $\left(\frac{L}{\rho}\right)_{air}^w$, and beam quality specifiers requires knowledge of many sets of the photon spectra. In general, $\%dd(10)_x$ and TPR_{10}^{20} can be calculated using a full Monte Carlo simulation of the particle transport through the geometry of the relevant accelerators and calculating the depth-dose distribution in a water phantom modelled at the bottom of the accelerator simulation.

This method is defined as Method A in Section 2.4, page 25. Although this is the most precise method, this way of calculation is not the most efficient if one already knows the realistic spectral distribution of the photon component of accelerator beam for the field size of interest (10x10 cm² at SSD=100 cm). To determine %*dd*(10)_x, depth-dose curves in water can be calculated with high precision using the BEAM component module CHAMBER to simulate a water phantom with a source option which represents a divergent source with known spectral distribution located at a certain distance (SSD) from the phantom. This latter method of calculations is defined as the Method B in the Section 2.4, page 28.

Using calculated or measured photon spectra, TPR_{10}^{20} and $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$ can be calculated for parallel circular beams using the DDSPR code, developed and benchmarked at NRC⁴⁵ (see Section 2.4.2, page 39).

2.3 Photon spectra used in calculations

An extensive number of measured and calculated photon spectra have been collected from clinical accelerators and from the NRC and NPL linacs. Some of them have been used for years as part of the NRC ENSRC collection and distributed together with the EGS4 user codes. They are described in detail in Appendix A, page 72. The other spectra have been calculated in the present work (NRC standard spectra and NRC soft and hard filtered spectra) using full simulations of the NRC linac with varying incident electron energies and flattening filter thicknesses. Details of the simulation are described in the Section 2.3.1.

Recently, Sheikh-Bagheri and Rogers^{36,46} did detailed Monte Carlo simulation of several commercial linear accelerators including Elekta SL25 6MV and 25

MV beams; Siemens KD 6 MV and 18 MV beams; Varian Clinac-4 MV and Clinac 2100C/2300C 6 MV, 10 MV, 15 MV and 18 MV photon beams. The simulations were done using the BEAM Monte Carlo system and benchmarked against measured data, (see section A.2 and Appendix A, for details). Photon spectra used in the present work have been calculated using Sheikh-Bagheri and Rogers^{36,46} set of parameters, which is slightly different from the parameters presented in their final paper,⁴⁶ in terms of mean energy of incident electron beam and the FWHM of the intensity distribution of the electron beam. These latter differences have been found not to make any significant change in the photon spectral distributions on the central axis. The phase-space files have been collected at 100 cm distance from the source for a 10x10 cm² field with typical statistical uncertainty for the fluence per energy bin of 0.5 - 1.5 %. The Sheikh-Bagheri and Rogers set of clinical spectra as well as the Mohan et al²⁶ spectra have been used to calculate $\%dd(10)_x$, TPR_{10}^{20} and $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$ values representative of calculated clinical beams. This latter set of spectra, also referred to as the Mohan spectra, have been calculated using the EGS3 Monte Carlo simulations of the Varian Clinac-4 (4 MV), -6 (6 MV), -18 (10 MV), -20 (15 MV), and -2500 (24 MV) medical accelerators, (see Section A.1 of Appendix A, page 73). These spectra have been widely used to represent typical clinical spectra for dosimetry related calculations.^{23,25,28,34}

Walters and Rogers⁴⁷ have used the BEAM code to model the photon beams of the National Physical Laboratory, UK (NPL). These beams have nominal energy from 4 to 19 MV. Two sets of the beams (“heavily” and “lightly” filtered) differ by the amount of additional aluminum filtration. Their phase space files have been used to obtain photon spectra on the central axis using the BEAMDP code.⁴¹ For the details of the simulations and comparison of their calculated depth-dose data to

those measured at NPL see Appendix A.4, page 75.

2.3.1 Calculation of photon spectra using the BEAM system

NRC 10 MV, 20 MV and 30 MV photon beams.

Sheikh-Bagheri et al⁴⁸ did detailed BEAM Monte Carlo simulations of the 10 and 20 MV photon beams of the NRC linac, which are used for standards work at NRC. The full Monte Carlo simulation of the linac includes the electron exit window, target, flattening filter, monitor chambers and collimators. The incident electron energy was known independently within 1% accuracy. The 10 and 20 MV photon beam simulations were benchmarked by comparing calculated and measured relative ionization distributions in water.⁴⁸ Dose distributions for benchmark purposes were calculated using a modified version of the EGS4 user code DOSXYZ. Dose has been converted to ionization by accounting for variation in the restricted stopping-power ratio, calculated for the phantom using the EGS4 user code SPRXYZ. At both energies, their calculated and the measured values of ionization on the central axis in the build-up region agreed within 1% of maximum ionization relative to the ionization at 10 cm depth. Elsewhere the agreement was well within a few tenths of a percent.

The NRC standard 10 and 20 MV photon spectra were calculated using the BEAM input files of Sheikh-Bagheri et al⁴⁸ and using those files as modified slightly for a simulation of the 30 MV NRC standard photon beam. The target for the 30 MV beam was a fully stopping Al block, 6.0 cm thick. The electron beam energy of the NRC linac is known to $\pm 1\%$ and the electron beam energy distribution in the 30 MV BEAM simulation was taken as a Gaussian distribution with a FWHM equal to 1% of the nominal energy. The electron beam incident on the target is scanned on the

surface of a cone with a half angle of 2.8° to obtain field flatness. The apex of the cone is positioned on the front surface of the target. It wobbles due to imperfections in the scanning foil inside a circle of 0.2 cm at the front surface of the target and the beam divergence is estimated to be less than 5 mrad (0.3°). The radial intensity profile of the electron beam has been measured 11.5 cm upstream of the exit window using a profile monitor and was estimated to be a Gaussian with a FWHM of 0.25 cm for the 30 MV beam [from Carl Ross, private communication]. The intensity distribution of the 30 MV electron beam was taken as a Gaussian with FWHM of 0.326 cm, as it was in the case of the 20 MV beam,⁴⁸ to include the effects of the electron beam divergence and focal spot wobbling. The BEAM code sampled the incident electrons from a radially symmetric intensity distribution defined at a given plane perpendicular to the central-axis (apex of the sweeping cone). For benchmarking purposes, values of TPR_{10}^{20} for all three beams have been calculated and compared to those measured at NRC,³¹ (see Section 2.4.1, page 29, and Table 2.5, page 34).

Selective bremsstrahlung splitting and range rejection technique were used in all three simulations. A value of $ESAVE=2$ MV for the range rejection was used everywhere except in the target, where range rejection was turned off.

Simulations of the linac were run in parallel on 600 MHz Pentium III CPUs. For the 10, 20 and 30 MV beams, the number of electron histories simulated was 5×10^6 , 4×10^6 and 2×10^6 , respectively. The phase-space files were collected at 100 cm distance from the source for a $10 \times 10 \text{ cm}^2$ field on the central axis. Phase-space files contained 6.1×10^6 , 19.5×10^6 and 30.0×10^6 particle entries for the 10, 20 and 30 MV beams, respectively, with more than 99% of them photons. Weights ranged from 0.005 to 1. Photon spectra were obtained for circular fields on the central axis with a radius of $r=5.6$ cm using the BEAMDP code.⁴¹ Typical uncertainties on the spectral

bins were 0.08-0.2% or 1-2% for the energy bins close to the maximum fluence of the spectra and for the high-energy bins, respectively. The 30 MV NRC standard calculated spectrum is shown in Figure 2.1 in the form of relative fluence, energy fluence and relative kerma fluence spectra. For the definitions of these terms see “Notation and Conventions” section, page xii.

Figure 2.1: 30 MV NRC standard spectrum for the 10x10 cm² field at 100 cm SSD calculated using BEAM. The heavy curve is the relative planar fluence per unit energy, the light curve is the energy fluence per unit energy and the dashed curve is collisional kerma weighted fluence per unit energy (for the definition of terms see “Notation and Conventions” section, page xii). All spectra are normalized to unity at their respective maxima. Typical statistical uncertainty per energy bin is 0.2 % at the spectrum maximum and less than 1.% at high energy bins.

NRC hard and soft beams.

In the early 90's, Ross et al did measurements in a series of beams generated at 10, 20, 25 and 30 MeV incident electron energy using a swept beam and a fully stopping target with or without extra aluminum filters.³⁰ The soft and hard photon beams ranging from 10 MV to 30 MV generated from NRC linac have been modelled

using the BEAM code by Yang et al.⁴⁹ The hard filtration refers to an additional 10-15 cm of Al located after the Al target. Monte Carlo simulated photon beams with hard and soft filtration have been validated by comparing tissue-phantom ratios $(\text{TPR}_{10}^{20})'$ calculated by the BEAM code to those measured by Ross et al.³⁰ Measured and calculated $(\text{TPR}_{10}^{20})'$ values were approximated by the ratio of the dose at 20 cm depth to the dose at 10 cm, $\frac{D(20)}{D(10)}$, corrected by $1/r^2$. The calculated and measured values agreed within the experimental uncertainty of 0.5%.

The spectra of the NRC hard and soft beams have been obtained using the BEAM input files from Yang et al.,⁴⁹ modified to define a field size $10 \times 10 \text{ cm}^2$ at 100 cm SSD ($10 \times 10 \text{ cm}^2$ at 120 cm SDD in original paper) and include a slab of air below the collimator. Simulations of these NRC hard and soft beams generated from the NRC linac included the Ti exit window, Al target, a square collimator and, in the case of the hardened beam, additional aluminum filtration below the target. Geometric characteristics of the beams used in the simulations are summarized in Table 2.1. Electron swept beams were simulated using the BEAM source option where the incident beam is a monoenergetic parallel circular beam of 0.26 cm radius, the axis of which sweeps the surface of an imaginary cone with a sweep angle as in Table 2.1.

Electron range rejection was turned off during simulations. To increase efficiency of the simulations, the selective bremsstrahlung splitting technique was used with typical values of $N_{\min}=30$, $N_{\max}=250$ and an effective field size of $20 \times 20 \text{ cm}^2$ at 100 cm SSD. The typical number of electron histories simulated was 1×10^6 for the soft beams and 2×10^6 for the hard beams. A typical phase space file included 25×10^6 particle entries for a 30 MV soft beam. Typical uncertainties on the spectral bins were 0.15-0.6% for the energy bins close to the maxima of the spectra and 2-4% for

Table 2.1: Geometry characteristics of the NRC soft and hard beams used in the Monte Carlo simulations.

Beam label, NAP	Target thickness, cm Al	Sweep angle, (°)	Hardener thickness, cm Al
NRC soft 10 MV	2.5	4.2	0
NRC soft 20 MV	4.5	4.2	0
NRC soft 25 MV	5.2	3.4	0
NRC soft 30 MV	6.0	2.8	0
NRC hard 20 MV	4.5	4.2	10.
NRC hard 25 MV	5.2	3.4	15.
NRC hard 30 MV	6.0	2.8	15.

high-energy bins, respectively. Calculated 20 MV soft and hard spectra are shown in Figure 2.2 as relative fluence, energy fluence and relative kerma fluence spectra. It can be seen from Figure 2.2 that 10 cm of aluminum filtration produces substantial hardening of the 20 MV spectrum (20 MV hard) compared to the bare 20 MV spectrum produced in the fully stopping Al target (20 MV soft).

2.4 Calculation of the beam quality specifiers and water to air stopping-power ratios $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$

Values of $\%dd(10)_x$ for all photon beams studied and TPR_{10}^{20} for the NRC standard beams have been obtained from depth-dose curves calculated using the BEAM code by two general methods of calculation, A and B, defined below. For each beam studied, the methods of calculation for $\%dd(10)_x$ and TPR_{10}^{20} values, or source of the data, are

Figure 2.2: Photon spectra calculated using BEAM for the NRC 20 MV a) soft and b) hard beams. Spectra have been calculated for the central axis ($r=0-5.6$ cm) at 100 cm SSD. The heavy curve is the relative planar fluence per unit energy, the light curve is the energy fluence per unit energy and the dashed curve is collisional kerma weighted fluence per unit energy (for the definition of terms see “Notation and Conventions” section, page xii). All spectra are normalized to unity at their respective maxima. Statistical uncertainties per energy bin are 0.15 and 0.3% at the spectra maxima for soft and hard spectra, respectively, and 2% high energy bins for both of them.

listed in Tables 2.2 and 2.3. The water phantom used in all BEAM simulations to calculate depth-dose curves in water has been modelled using the BEAM component module CHAMBER. It is described in Section 2.4.1, page 29, in detail. Section 2.4.1 also contains the details of the depth-dose curve calculations and the BEAM calculated values of $\%dd(10)_x$ and TPR_{10}^{20} .

For all other beams studied, except the NRC soft and hard beams, values of TPR_{10}^{20} have been calculated using photon fluence spectra and the DDSPR code⁴⁵ which is described in the Section 2.4.2, page 39.

Water to air stopping-power ratio, $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$, for all beams studied have been calculated using the DDSPR code. Details of the TPR_{10}^{20} and $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$ calculations are described in Section 2.4.2 and their values are listed in tables therein.

Calculated values of TPR_{10}^{20} for the NRC soft and hard beams have been taken from the original paper of Yang et al.⁴⁹ They are discussed in more detail in Section 2.4.2, page 44.

Calculated values of $\%dd(10)_x$ for the NPL beams are discussed in more detail in Section 2.4.1, page 36, and compared to the $\%dd(10)_x$ values calculated by Walters and Rogers.⁴⁷

Method A: Phantom as a part of accelerator

As mentioned in Section 2.3.1, values of $\%dd(10)_x$ and TPR_{10}^{20} can be obtained from a depth-dose curve in a water phantom using a full Monte Carlo simulation of the geometry of the accelerator and a water phantom modelled at the bottom of the accelerator simulation. Values of $\%dd(10)_x$ and TPR_{10}^{20} for NRC standard beams and $\%dd(10)_x$ for NRC soft and hard beams have been modelled this way, having modified the input files used for the photon spectra calculations (see Section 2.3.1). The values

Table 2.2: Method of calculation, or the source for the data, for six of the beam sets studied. Method A means a full Monte Carlo simulation of the accelerator geometry with a water phantom as a part of accelerator (described in Section 2.4, page 25 in detail). Method B refers to BEAM depth-dose curve calculations using the CHAMBER CM as a water phantom with point source incident (see Section 2.4, page 28, for details). All stopping-power ratios $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$ have been calculated using the DDSPR code, (see Section 2.4.2), and spectra calculated by BEAM, (see Section 2.3.1).

Beam label, NAP, MV	%dd(10) _x	TPR ₁₀ ²⁰	Beam label, NAP, MV	%dd(10) _x	TPR ₁₀ ²⁰
NRC st 10	A	A	S-B Varian 4 MV	A,B	DDSPR
NRC st 20	A	A	S-B Varian 6 MV	B	DDSPR
NRC st 30	A	A	S-B Varian 10 MV	B	DDSPR
NRC soft 10	A	Yang et al ⁴⁹	S-B Varian 15 MV	A,B	DDSPR
NRC soft 20	A	Yang et al ⁴⁹	S-B Varian 18 MV	B	DDSPR
NRC soft 25	A	Yang et al ⁴⁹	S-B Siemens 6 MV	B	DDSPR
NRC soft 30	A	Yang et al ⁴⁹	S-B Siemens 18 MV	B	DDSPR
NRC hard 20	A	Yang et al ⁴⁹	S-B Elekta 6 MV	B	DDSPR
NRC hard 25	A	Yang et al ⁴⁹	S-B Elekta 25 MV	B	DDSPR
NRC hard 30	A	Yang et al ⁴⁹	racetrack 30	B	DDSPR
Mohan 4	B	DDSPR	racetrack 50	B	DDSPR
Mohan 6	B	DDSPR			
Mohan 10	B	DDSPR			
Mohan 15	B	DDSPR			
Mohan 24	B	DDSPR			

Table 2.3: Method of calculation of beam quality specifiers for the NPL calculated beams⁴⁷ and NRC measured beams.⁵⁰ All notations as in Table 2.2, page 26.

Beam label, NAP, MV	$\%dd(10)_x$	TPR_{10}^{20}	Beam label, NAP, MV	$\%dd(10)_x$	TPR_{10}^{20}
NPL heavily f 4	B	DDSPR	NRC m Al 10	B	DDSPR
NPL heavily f 6	B	DDSPR	NRC m Al 15	B	DDSPR
NPL heavily f 8	B	DDSPR	NRC m Al 20	B	DDSPR
NPL heavily f 10	B	DDSPR	NRC m Al 25	B	DDSPR
NPL heavily f 12	B	DDSPR	NRC m Al 30	B	DDSPR
NPL heavily f 16	B	DDSPR	NRC m Pb 10	B	DDSPR
NPL heavily f 19	B	DDSPR	NRC m Pb 15	B	DDSPR
NPL lightly f 4	B	DDSPR	NRC m Pb 20	B	DDSPR
NPL lightly f 6	B	DDSPR	NRC m Pb 25	B	DDSPR
NPL lightly f 8	B	DDSPR	NRC m Pb 30	B	DDSPR
NPL lightly f 10	B	DDSPR	NRC m Be 15	B	DDSPR
NPL lightly f 12	B	DDSPR	NRC m Al + Al 10	B	DDSPR
NPL lightly f 16	B	DDSPR	NRC m Al + Al 20	B	DDSPR
NPL lightly f 19	B	DDSPR			

of $\%dd(10)_x$ were calculated for a $10 \times 10 \text{ cm}^2$ field size at $\text{SSD}=100 \text{ cm}$ and values of TPR_{10}^{20} calculated at $\text{SDD}=100 \text{ cm}$. Selective bremsstrahlung splitting has been used in Method A depth-dose curve calculations with the same parameters as used for the spectral calculations, except where it is stated explicitly. To increase the efficiency of in-phantom calculations, electrons and photons entering the phantom have been split 100 times. This variance reduction technique was designed primarily for photons and was originally introduced to allow splitting in phantoms placed at the bottom of an accelerator.⁴⁴

To separate photon components of the depth-dose curve for the $\%dd(10)_x$ calculations, BEAM's LATCH variable feature was used. One can select the charge of the particles entering water phantom to be defined as a "contaminant". Zero charge means that the photons will be identified upon entering the phantom and this mark will be passed onto their descendants. The dose contributed by the photons upon entering the phantom and their descendants is then scored separately in each dose zone.

Values of $\%dd(10)_x$ were calculated from the photon-only depth-dose curve by taking the dose at 10 cm depth in the phantom and dividing by the dose at the peak. In the case of TPR_{10}^{20} calculations, total doses at depths of 20 and 10 cm in the phantom at constant $\text{SDD}=100 \text{ cm}$ have been calculated in two separate calculations for two different values of SSD.

Method B: Spectra incident on a phantom

To determine $\%dd(10)_x$, depth-dose curves in water can be calculated using the BEAM component module CHAMBER to model a water phantom with a point source incident. For the photon beams from clinical accelerators simulated by Sheikh-Bagheri

and Rogers⁴⁶ and Mohan et al,²⁶ MM50 racetrack microtron calculated spectra and bremsstrahlung spectra measured at NRC by Faddegon et al,⁵⁰ values of $\%dd(10)_x$ have been calculated this way. The radiation source in these simulations was modelled by an isotropic point source located on the Z-axis at a distance of 100 cm and a circular field of radiation with radius of 5.6 cm (or square field 10x10 cm²). The energy spectrum file was read from files with a standard ENSRC format. The code randomly distributes incident particle energy uniformly across each energy bin. No electron rejection technique was used in these simulations although it would have substantially improved the efficiency of the calculations.

2.4.1 Calculation of the $\%dd(10)_x$ and TPR_{10}^{20} using BEAM

Water phantom used in the depth-dose curve calculations.

The water phantom for depth-dose curve calculations has been modelled using the BEAM component module CHAMBER. It had a radius of 28.2 cm and a depth of 28.5 cm. Absorbed doses per incident particle have been scored in circular regions on the central axis, see Figure 2.3. The radius of the scoring zone varied for different calculations and is listed among simulation parameters in Tables 2.4, 2.5, 2.6 and 2.7. Its choice depended, in general, on the spatial distribution of the photon fluence at the phantom surface, so that the scoring region was well within the flat part of the distribution. The thicknesses of the 30 first scoring regions were 0.3 cm followed by one region with thickness of 0.5 cm, and 19 regions with thickness 1 cm. The fine structure for the first 9 cm of the phantom and a requirement that the statistics on the calculated dose at each depth be within few tenths of a percent, led to a detailed calculation of the depth-dose curve about d_{max} and an unbiased choice of

the maximum dose D_{max} , since the depth of the maximum dose, d_{max} , for all studied photon beams is well within the first 9 cm of water. To increase the efficiency of the dose calculation at depths beyond d_{max} , 1 cm thick scoring bins were centered at 10 cm and 20 cm.

Calculation of depth-dose distributions for NRC 10 MV, 20 MV and 30 MV standard beams. Method A.

The values of $\%dd(10)_x$ and TPR_{10}^{20} for the NRC 10, 20 and 30 MV standard beams were calculated by Method A, (see page 25). Electron range rejection with fixed ECUTRR and ESAVE=2 MeV was used for these simulations. The selective bremsstrahlung splitting technique was applied for 30 MV beam with the minimum and maximum number of bremsstrahlung photons $N_{min}=10$, $N_{max}=400$.

Figure 2.4 presents a typical depth dose distributions for the 30 MV standard beam where total dose distribution and dose distribution due to the photons only have been plotted separately. It can be seen from Figure 2.4 that contaminant electrons which have been produced by photon interactions in the accelerator geometry cause these two curves to be substantially different at depths close to d_{max} (2% of the total dose at d_{max} is contributed by contaminant electrons) and the curves are essentially the same at a depth of 10 cm and beyond this depth. Results of the $\%dd(10)_x$ calculations with estimated uncertainties and the parameters of the Monte Carlo calculations such as number of electron histories simulated, CPU time of calculations and the radius of the scoring zone are summarized in Table 2.4.

Calculated TPR_{10}^{20} and BEAM simulation parameters are presented in Table 2.5. Values of TPR_{10}^{20} , and their uncertainties, measured at NRC³¹ are given for comparison. Calculated TPR_{10}^{20} values are found to be in reasonable agreement with

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Figure 2.3: Water phantom used to calculate depth-dose curves using the BEAM CHAMBER component module. Regions on the central axis, where absorbed dose is scored, are outlined by the thick lines. The radius of the scoring zone varies for different calculations and is listed among simulation parameters in Tables 2.4, 2.5, 2.6 and 2.7. The thicknesses of the first 30 scoring regions are 0.3 cm, followed by one region with thickness of 0.5 cm, and 19 regions with thickness 1 cm.

Figure 2.4: Total depth-dose distribution and depth-dose component due to the photons only have been calculated using a full simulation of the NRC 30 MV standard beam and the BEAM component module CHAMBER.

Table 2.4: Calculated values of $\%dd(10)_x$ and BEAM simulation parameters for depth-dose calculations using a full simulation of the NRC linac and a CHAMBER depth-dose phantom attached to the bottom of accelerator. Values of $\%dd(10)_x$ are presented with calculational uncertainty in parenthesis. 69.05(9) means $\%dd(10)_x = (69.05 \pm 0.09)\%$ where 0.09 is the one standard deviation uncertainty estimated from the Monte Carlo run. Simulations were done on 600 MHz Pentium III CPUs. Range rejection was applied in all cases except *. Simulations of the 30 MV NRC standard beam and the 30 MV NRC hard beam, ^s, used selective bremsstrahlung splitting with $N_{min}=10$, $N_{max}=400$ instead of $N_{min}=30$, $N_{max}=250$ as in all other simulations.

Energy, filtration	# of histories	CPU time, hrs	r, cm	$\%dd(10)_x$
NRC standard beams				
10	2.0×10^8	78	3.	69.05(9)
20	2.0×10^8	302	3.	79.94(5)
30	2.0×10^8	159 ^s	3.	88.0(2)
NRC soft and hard beams, see Section 2.3.1				
NRC soft 10	1.0×10^8	117*	4.	68.5(1)
NRC soft 20	2.0×10^8	157*	4.	79.7(1)
NRC soft 25	8.6×10^6	527	4.	84.04(7)
NRC soft 30	3.6×10^6	249	3.	87.7(2)
NRC hard 20	2.0×10^7	433*	4.	81.98(9)
NRC hard 25	5.0×10^6	86	4.	86.8(1)
NRC hard 30	5.0×10^6	164 ^s	4.	90.3(1)

Table 2.5: Values of TPR_{10}^{20} of the NRC standard beams calculated using full simulation of the NRC linac for a $10 \times 10 \text{ cm}^2$ field at $SDD = \text{const}$ and the BEAM simulation parameters as for depth-dose calculation. TPR_{10}^{20} results are presented with calculational uncertainty in parenthesis as in Table 2.4. Measured TPR_{10}^{20} are given for comparison with their measurement uncertainties as in original paper.³¹ Stopping-power ratios $\left(\frac{\bar{L}}{\rho}\right)_{\text{air}}^w$ have been calculated using the DDSPR code, (see Section 2.4.2), and spectra calculated by BEAM, (see Section 2.3.1). Typical number of histories and CPU time of calculations are related to a calculation of total dose at 20 cm depth in water at $SDD = 110 \text{ cm}$, $D(20)$, or total dose at 10 cm depth in water at $SDD = 110 \text{ cm}$, $D(10)$, from which TPR_{10}^{20} was estimated, so that actual time of calculations is approximately two times longer. Range rejection was applied with $ESAVE = 2 \text{ MeV}$ except rr where range rejection was used with $ESAVE = 5 \text{ MeV}$.

Energy, MV	number of histories	CPU time, hrs	calculated TPR_{10}^{20}	measured TPR_{10}^{20}	$\left(\frac{\bar{L}}{\rho}\right)_{\text{air}}^w$
10	5.0×10^6	19	0.678(2)	0.682(1)	1.1123
20	2.5×10^6	29	0.755(2)	0.758(1)	1.0903
30	2.2×10^6	147 ^{rr}	0.793(2)	0.794(1)	1.0726

the measured data. Stopping-power ratios $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$ in Table 2.5 have been calculated using the DDSPR code (see section 2.4.2, page 39) and using spectra calculated by BEAM (see section 2.3.1, 19).

Calculation of $\%dd(10)_x$ for NRC soft and hard beams. Method A.

The values of $\%dd(10)_x$ for the soft and hard NRC beams were calculated by Method A, (see page 25). The number of electron histories simulated are listed in the Table 2.4 along with CPU times of calculations and the radii of the scoring zones. In the case of the 25 and 30 MV soft beams and 25 and 30 MV hard beams, the electron range rejection technique was used with set ECUTRR and ESAVE=5 MeV everywhere except in the target where ESAVE was set equal to 2 MeV. In all other beam simulations electron range rejection was not used. Electrons and photons entering the phantom have been split 100 times in all cases except the 10 and 20 MV soft filtered beams. Calculated $\%dd(10)_x$ values for the NRC linac soft and hard beams are listed in Table 2.4 with their estimated uncertainties.

Calculation of $\%dd(10)_x$ using photon spectra. Method B.

For the four other sets of photon beams, including spectra from clinical accelerators simulated by Sheikh-Bagheri and Rogers⁴⁶ and Mohan et al,²⁶ MM50 racetrack microtron calculated spectra and bremsstrahlung spectra measured at NRC by Faddegon et al,⁵⁰ values of $\%dd(10)_x$ have been calculated using Method B, (see page 28). Sheikh-Bagheri and Rogers' photon spectra calculated for a 10x10 cm² field at 100 cm SSD have been converted to the ENSRC format from the XMGR format files created as output of BEAMDP. The Mohan, racetrack and NRC measured spectra have been taken from the ENSRC collection of spectra developed at NRC, (see Appendix A for details). Calculated $\%dd(10)_x$ values with estimated 1 σ uncertainties and simulation

parameters are listed in Tables 2.6 and 2.7. To verify our calculations of $\%dd(10)_x$ for Sheikh-Bagheri and Rogers' clinical spectra by Method B, values of $\%dd(10)_x$ were calculated for the 4 MV Varian Clinac-4 and 15 MV Varian Clinac 2100C accelerators using a full Monte Carlo simulation of those accelerators with Sheikh-Bagheri and Rogers' input files modified to attach a water phantom at SSD=100 cm (Method A). Electron range rejection was turned off in both simulations. Selective bremsstrahlung splitting with $N_{min}=40$, $N_{max}=250$ in a field size of 20x20 cm² at 100 cm SSD was used in both cases. In the case of the 15 MV beam, electrons and photons were split 100 times upon entering water phantom to increase efficiency of in-phantom calculations. The radius of the scoring zone was 4 cm in both simulations. The number of histories simulated was 1×10^8 for the 15 MV beam and 2.5×10^6 for the 4 MV beam, respectively. Simulations ran in parallel on five 600 MHz Pentium III CPUs. Values of $\%dd(10)_x$ calculated using the full Monte Carlo simulation of the accelerator geometry and their 1σ uncertainties were $62.2 \pm 0.3 \%$ for the Clinac-4 4 MV beam and $77.5 \pm 0.2 \%$ for the Clinac 2100C 15 MV beam. They agree with the $\%dd(10)_x$ values calculated using Method B within the statistics of the calculations (Table 2.6). This implies any spectral variations across the beam have no significant effect.

Calculated $\%dd(10)_x$ for NPL photon beams. Method B.

For NPL heavily and lightly filtered photon beams, values of $\%dd(10)_x$ have been calculated using NPL spectra, obtained from Walters and Rogers' phase space files collected at 118-120 cm distance from the source (Method B). Values of $\%dd(10)_x$ and BEAM simulation parameters are listed in Table 2.8. Monte Carlo calculated values of $\%dd(10)_x$ from the original report of Walters and Rogers⁴⁷ are listed in the second column of Table 2.8 for comparison. Walters and Rogers' values of $\%dd(10)_x$ (see Table 7 therein⁴⁷), have been calculated using photon spectra generated by BEAM

Table 2.6: Calculated values of $\%dd(10)_x$ for the clinical beams and BEAM simulation parameters for depth-dose calculations of $\%dd(10)_x$ using a CHAMBER depth-dose phantom and photon spectra described in Appendix A, page 72. Simulations were done on 600 MHz Pentium III CPUs except * which were on 1 GHz AMD Athlon CPUs.

NAP, MV	# of histories	CPU time, hrs	r, cm	$\%dd(10)_x$
Mohan et al, ²⁶ Appendix A, page 73				
4	2.2×10^8	2.6*	2.	63.2(1)
6	2.0×10^8	2.6*	3.	66.87(8)
10	5.0×10^7	1.5	4.	73.3(2)
15	5.0×10^7	1.6	2.5	78.9(2)
24	2.0×10^8	6.6	3.	86.09(7)
Sheikh-Bagheri and Rogers, ⁴⁶ Appendix A, page 74				
Varian 4	5×10^7	3.3	4.	62.1(1)
Varian 6	1.0×10^8	5.3	4.	66.15(7)
Varian 10	1.5×10^8	8.9	4.	73.51(6)
Varian 15	2.0×10^8	12.7	4.	77.28(8)
Varian 18	1.5×10^8	10.2	4.	81.12(8)
Siemens 6	1.0×10^7	14.2	4.	66.7(1)
Siemens 18	2.0×10^8	12.7	4.	77.62(6)
Elekta 6	1.0×10^8	14.3	4.	66.8(1)
Elekta 25	2.0×10^8	38.7	4.	82.66(7)
MM50 racetrack microtron spectra, ²⁵ Appendix A, page 75				
30	2.0×10^8	3.9*	4.	88.17(6)
50	2.0×10^8	8.2	4.	95.17(7)

Table 2.7: Values of $\%dd(10)_x$ for the measured at NRC photon spectra⁵⁰ calculated using Method B and the BEAM Monte Carlo system. Simulations were done on 600 MHz Pentium III CPUs except * which were on 1 GHz AMD Athlon CPUs.

Faddegon et al, ⁵⁰ Appendix A, page 76				
Energy, filtration	# of histories	CPU time, hrs	r, cm	$\%dd(10)_x$
NRC m Al 10MV	2.0×10^8	4.2	2.	70.5(2)
NRC m Al 15MV	2.0×10^8	2.4*	2.	76.8(2)
NRC m Al 20MV	2.0×10^8	2.6*	2.	82.1(2)
NRC m Al 25MV	2.0×10^8	2.8*	2.	86.4(2)
NRC m Al 30MV	2.0×10^8	3.0*	2.	89.6(2)
NRC m Pb 10MV	2.0×10^8	4.1	2.	71.4(1)
NRC m Pb 15MV	2.0×10^8	4.9	2.	77.3(2)
NRC m Pb 20MV	2.0×10^8	5.6	2.	81.3(1)
NRC m Pb 25MV	2.0×10^8	5.4	2.	85.4(1)
NRC m Pb 30MV	2.0×10^8	5.6	2.	88.3(1)
NRC m Be 15MV	2.0×10^8	5.0	2.	76.8(1)
NRC m Al + Al 10MV	2.0×10^8	5.5	2.	74.7(1)
NRC m Al + Al 20MV	2.0×10^8	3.1*	2.	85.3(1)

and used as input to DDSPR. In addition to $1/r^2$ correction from a parallel beam to a point source automatically done by DDSPR, their $\%dd(10)_x$ values have been corrected using the K_{PS} correction factor determined by Yang et al.⁴⁹ This factor takes into account phantom scatter effects and depends on the value of $\%dd(10)_x$. Although in some cases the difference between their $\%dd(10)_x$ and the BEAM calculated $\%dd(10)_x$ is as big as 1.2% this does not significantly affect the principal issue of the present work, i.e., if $\%dd(10)_x$ is a unique beam quality specifier in terms of choosing a unique value of stopping power water to air ratios compared to TPR_{10}^{20} . This can be seen from Figure 2.5, where both sets of $\%dd(10)_x$ values are plotted vs. stopping power ratios calculated using the DDSPR code and NPL spectra. The two sets of data behave in a very similar fashion. These results do suggest a beam quality dependence of K_{PS} .

2.4.2 Calculation of TPR_{10}^{20} and $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$ using DDSPR

DDSPR main features and algorithm.

The DDSPR code, which was developed and benchmarked at NRC,⁴⁵ calculates photon depth-dose curves and stopping-power ratios for an arbitrary photon fluence spectrum. The code uses a data base of depth-dose distributions and water to air stopping-power ratios generated for 36 monoenergetic photon beams with energies from 50 keV to 60 MeV and 8 beam radii ranged from 2 cm to effectively infinite. Depth-dose distributions for an arbitrary input photon fluence spectrum are calculated by convolving the fluence spectrum and monoenergetic depth-dose data. Depth-dose distributions for the monoenergetic data base were calculated by the EGS4 user-codes DOSRZ. Depth-dose data have been calculated to a one standard

Table 2.8: Values of $\%dd(10)_x$ for $10 \times 10 \text{ cm}^2$ field and SSD=100 cm for the NPL heavily and lightly filtered beams calculated using the Method B, and BEAM simulation parameters. Values of $\%dd(10)_x$ calculated by Walters and Rogers⁴⁷ (second column) are given for comparison (see discussion in Section 2.4.1, page 29). Simulations were done on 600 MHz Pentium III CPUs except * which were on 1 GHz AMD Athlon CPUs. Range rejection was not applied except *rr* where range rejection was used with ESARE=2 MeV.

Spectrum label, NAP	$\%dd(10)_x$ Walters and Rogers ⁴⁷	# of histo- ries	CPU time, hrs	r, cm	$\%dd(10)_x$ BEAM, CHAM- BER
NPL heavily f 4 MV	63.0	2.0×10^8	4.2	2.	62.5(1)
NPL heavily f 6 MV	67.2	2.0×10^8	4.5	2.	67.4(1)
NPL heavily f 8 MV	71.7	2.0×10^8	2.1*, <i>rr</i>	3.	71.4(1)
NPL heavily f 10 MV	75.2	2.0×10^8	2.7*	2.5	74.6(1)
NPL heavily f 12 MV	77.0	2.0×10^8	2.3*, <i>rr</i>	3.	76.9(1)
NPL heavily f 16 MV	80.8	2.0×10^8	4.5 <i>rr</i>	3.	80.7(1)
NPL heavily f 19 MV	83.2	2.0×10^8	7.5 <i>rr</i>	3.	83.16(4)
NPL lightly f 4 MV	60.3	2.0×10^8	7.3	2.	60.1(1)
NPL lightly f 6 MV	65.8	2.0×10^8	4.2 <i>rr</i>	3.	65.0(1)
NPL lightly f 8 MV	69.2	2.0×10^8	3.8	3.	68.6(1)
NPL lightly f 10 MV	72.0	2.0×10^8	2.5*	2.5	71.5(1)
NPL lightly f 12 MV	74.4	2.0×10^8	2.5*	2.5	73.9(1)
NPL lightly f 16 MV	78.2	2.0×10^8	2.8*	3.	77.9(1)
NPL lightly f 19 MV	80.7	2.0×10^8	4.5*	3.	80.5(1)

Figure 2.5: Values of $\%dd(10)_x$ for the NPL beams, calculated by Walters and Rogers⁴⁷ using DDSPR and the K_{ps} correction factor, shown as triangles-up, and calculated using BEAM and the same spectra, shown as triangles-down, vs. $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$ calculated using DDSPR and the same spectra. Values of $\%dd(10)_x$ vs. $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$ for Mohan et al²⁶ spectra are shown for comparison.

deviation uncertainty on the dose better than 0.5 % (often 0.2%) on the descending part of the depth-dose curve. Stopping-power ratios for the monoenergetic beams relative to the depth were calculated by the user-code SPRRZ based on the ICRU 37 stopping powers. One standard deviation uncertainty of the $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$ values in each bin was less than 0.05% in the energy range 0.050 - 20 MeV and less than 0.15 % in the range 25 - 60 MeV in the descending part of the depth-dose curves. The basic DDSPR algorithms were developed for circular parallel beams of photons incident normally on the water phantom. Photon spectra are assumed not to vary across a beam. Once results for parallel beams are obtained, the depth-dose curves for point source beams at a finite SSD are calculated using a simple $1/r^2$ correction. The stopping-power ratios are not corrected for the finite SSD. Having high statistical precision for each energy in the data base, calculated TPR_{10}^{20} values are expected to have statistical precision better than 0.6 % for monoenergetic beams and about 0.2 % for broad spectra.⁴⁵ DDSPR calculates TPR_{10}^{20} values as a dose ratio at 20 and 10 cm for a plane parallel beam. This is equivalent to the TPR_{10}^{20} definition of a ratio of doses at two different depths with constant source-detector distance (SDD).³⁴ The depth-dose curve is least square fitted by DDSPR to an exponential function for depths between 10 and 20 cm. The fitting is assumed to increase statistical precision of the TPR_{10}^{20} calculations although in all studied cases, fitted TPR_{10}^{20} values do not differ by more than 0.08% from the value obtained by a simple ratio of the doses at two depths. This suggests that statistical precision is somewhat better than the 0.2 % estimated uncertainty of TPR_{10}^{20} for a broad beam.⁴⁵

Calculation of TPR_{10}^{20} and $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$.

Values of TPR_{10}^{20} for all beams, except the NRC standard spectra and the NRC soft and hard spectra, have been calculated using the DDSPR code for plane

Table 2.9: Values of TPR_{10}^{20} for NRC soft and hard beams calculated by Yang et al⁴⁹ using full Monte Carlo simulations of the NRC linac. Values of $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$ were calculated using the DDSPR⁴⁵ code and photon spectra calculated using BEAM, (see Section 2.3.1, page 19). Values of TPR_{10}^{20} were expected to have statistical precision about 0.2 % for broad spectra and values of $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$ better than 0.05% in the energy range 0.050 - 20 MeV and better than 0.15 % in the range 25 - 60 MeV.⁴⁵

Spectrum label, NAP	TPR_{10}^{20}	$\left(\frac{\bar{L}}{\rho}\right)_{air}^w$
NRC soft 10 MV	0.6772	1.113
NRC soft 20 MV	0.7525	1.091
NRC soft 25 MV	0.7729	1.081
NRC soft 30 MV	0.7893	1.073
NRC hard 20 MV	0.7816	1.084
NRC hard 25 MV	0.8050	1.074
NRC hard 30 MV	0.8142	1.065

parallel beams with a radius of 5.6 cm and fluence spectra described in Appendix A. Water to air stopping-power ratios, $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$, for all 12 studied sets of photon spectra were calculated using DDSPR and photon spectra generated by BEAM, (see Section 2.3.1), and spectra from the EGS4 ENSRC distribution, (see Appendix A, Section A). Spectra generated using BEAM in the present work have been converted to the SPECH format, required by DDSPR, using the XVGR2SPECH routine. Values of TPR_{10}^{20} calculated using DDSPR are listed in Tables 2.10, 2.11 and 2.12.

For the NRC soft and hard spectra TPR_{10}^{20} values calculated by Yang et al⁴⁹ using a full Monte Carlo simulation of the NRC linac have been collected from the original paper,⁴⁹ and are listed in Table 2.9. Values of $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$ calculated using DDSPR for all spectra studied are listed in Tables 2.5, 2.10, 2.11, 2.12 and 2.9.

2.5 FLURZnrc calculations

FLURZnrc is an NRC user-code based on the EGSnrc Monte Carlo system.^{51,52} Like its predecessor FLURZ, it is designed to score particle fluence in a generalized cylindrical (RZ) geometry. The geometry of any RZ NRC user codes consists of NZ depth slabs or regions which are separated by NZ+1 planar boundaries and NR radial regions or rings defined by their outer radii. Each geometrical region can be associated with an arbitrary material. There are 15 source geometries available in the RZ NRC user codes and particles can be sampled from an arbitrary energy distribution supplied by the user. FLURZnrc calculates the average particle fluence in the volume scoring the total particle path length per unit volume. It has been formally proved that this quantity is equivalent to the ICRU definition of particle fluence,^{1,2} (see also “Notation and Conventions” section, page xii). The average energy of particles in

Table 2.10: Values of TPR_{10}^{20} and $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$ for the spectra from clinical accelerators, (see Appendix A, page 72), calculated using the DDSR⁴⁵ code. Values of TPR_{10}^{20} were expected to have a statistical precision about 0.2 % for broad spectra and values of $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$ better than 0.05% in the energy range 0.050 - 20 MeV and better than 0.15 % in the range 25 - 60 MeV.⁴⁵

Spectrum label, NAP	TPR_{10}^{20}	$\left(\frac{\bar{L}}{\rho}\right)_{air}^w$
Mohan et al, ²⁶ Appendix A, page 73		
Mohan 4 MV	0.6255	1.127
Mohan 6 MV	0.6679	1.120
Mohan 10 MV	0.7287	1.106
Mohan 15 MV	0.7617	1.094
Mohan 24 MV	0.8041	1.075
Sheikh-Bagheri and Rogers, ⁴⁶ Appendix A, page 74		
S-B Varian 4 MV	0.6200	1.128
S-B Varian 6 MV	0.6617	1.120
S-B Varian 10 MV	0.7314	1.105
S-B Varian 15 MV	0.7530	1.097
S-B Varian 18 MV	0.7763	1.088
S-B Siemens 6 MV	0.6676	1.119
S-B Siemens 18 MV	0.7591	1.095
S-B Elekta 6 MV	0.6702	1.119
S-B Elekta 25 MV	0.7894	1.083
MM50 racetrack microtron spectra, ²⁵ Appendix A, page 75		
racetrack 30 MV	0.7950	1.073
racetrack 50 MV	0.8484	1.054

Table 2.11: Values of TPR_{10}^{20} and $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$ calculated using the DDSR code for the thick target bremsstrahlung spectra measured at NRC by Faddegon et al,⁵⁰ see Appendix A, page 76. “+ Al” means additional aluminum filtration, as described in Section A.5. Values of TPR_{10}^{20} were expected to have a statistical precision about 0.2 % for broad spectra and values of $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$ better than 0.05% in the energy range 0.050 - 20 MeV and better than 0.15 % in the range 25 - 60 MeV.⁴⁵

Spectrum label, NAP	TPR_{10}^{20}	$\left(\frac{\bar{L}}{\rho}\right)_{air}^w$
NRC meas. Al 10 MV	0.6929	1.111
NRC meas. Al 15 MV	0.7396	1.097
NRC meas. Al 20 MV	0.7679	1.086
NRC meas. Al 25 MV	0.7891	1.076
NRC meas. Al 30 MV	0.8039	1.068
NRC meas. Pb 10 MV	0.7012	1.111
NRC meas. Pb 15 MV	0.7415	1.098
NRC meas. Pb 20 MV	0.7650	1.088
NRC meas. Pb 25 MV	0.7801	1.081
NRC meas. Pb 30 MV	0.7938	1.074
NRC meas. Be 15 MV	0.7403	1.097
NRC meas. Al + Al 10 MV	0.7465	1.102
NRC meas. Al + Al 20 MV	0.8027	1.076

Table 2.12: Values of TPR_{10}^{20} and $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$ for NPL heavily and lightly filtered spectra, (see Appendix A, Section A.4, page 75), calculated using the DDSR⁴⁵ code. Values of TPR_{10}^{20} were expected to have a statistical precision about 0.2 % for broad spectra and values of $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$ better than 0.05% in the energy range 0.050 - 20 MeV and better than 0.15 % in the range 25 - 60 MeV.⁴⁵

Spectrum label, NAP	TPR_{10}^{20}	$\left(\frac{\bar{L}}{\rho}\right)_{air}^w$
NPL heavily f 4	0.6163	1.127
NPL heavily f 6	0.6641	1.120
NPL heavily f 8	0.7130	1.111
NPL heavily f 10	0.7441	1.103
NPL heavily f 12	0.7581	1.098
NPL heavily f 16	0.7791	1.088
NPL heavily f 19	0.7894	1.083
NPL lightly f 4	0.5830	1.129
NPL lightly f 6	0.6453	1.122
NPL lightly f 8	0.6776	1.116
NPL lightly f 10	0.7009	1.110
NPL lightly f 12	0.7217	1.105
NPL lightly f 16	0.7472	1.097
NPL lightly f 19	0.7610	1.091

each region is calculated by scoring particle energies at the middle of each step multiplied by the step path length and subsequently dividing the sum of those scored quantities by the total particle path length in the region.

Using calculated photon spectra for the 20 MV and 25 MV soft and hard beams of the NRC linac , (see Section 2.3.1, page 19), average energies of the electron and photon fluence spectra have been calculated in radial depth bins on the central axis of the water phantom, shown in Figure 2.6. The water phantom used in the

Figure 2.6: Geometry of the water phantom used in FLURZnrc calculations. The water phantom consists of a cylinder of water with a radius of 15 cm and a depth of 30 cm. The radius of the scoring zone on the central axis is 2 cm and depth bins are 1 cm thick. The radiation source used in the simulations was a point source at a distance of 100 cm from the front of the phantom (along z-axis) with a beam radius 5.6 cm defined at the phantom surface (ISOURCE=1). The image has been produced using the `previewRZ` routine.⁵²

present calculations consists of a cylinder of water with radius of 15 cm and depth of the 30 cm. The radius of the scoring zone on the central axis is 2 cm and depth

bins are 1 cm thick. The radiation source used in the simulations was a point source (ISOURCE=1) at a distance 100 cm from the front of the phantom with a beam radius 5.6 cm defined on the phantom surface. The energy distribution of the source was the photon spectra for the 20 MV and 25 MV soft and hard beams. Electrons and photons were tracked down to the 0.7 and 0.01 MeV cut-off energies respectively. The default PRESTA-II algorithm was used to take into account lateral and longitudinal correlations in a condensed history step. Spin effects have been turned on to account for relativistic spin effects in the multiple scattering cross sections. Bound Compton scattering options have been used to account for bound Compton scattering instead of pure Klein-Nishina Compton scattering and atomic relaxation option for relaxation simulation which allows creation and following of the fluorescent photons and Auger electrons after photo-electric and Compton scattering events. Variance reduction techniques have not been applied in the simulations. The number of photon histories simulated was 1×10^7 in each case. Typical statistical uncertainty on the average energy of the particle spectra in the depth bins with radius 2 cm on the central axis was better than 1% for depth bins beyond a few centimeters for electrons and 0.1 to 0.2% for all depth bins for photons. Results of FLURZnrc calculations for four beams of the NRC linac are listed in Table 2.13 and plotted in Figures 2.7a and 2.7b. In Table 2.13, the average energy of the electron $\bar{E}_{e^-}$ and photon $\bar{E}_\gamma$ fluence spectra for the depth bin between 10 and 11 cm on the central axis ($r=0-2$ cm, CA) and off-axis ($r=2-15$ cm, OA) in the water phantom, shown in Figure 2.6, are listed together with their relative standard deviations in parenthesis. In Figure 2.7a, 2.7b the average energy of the electron (a) and photon (b) spectra on the central axis are shown versus depth in the phantom.

Figure 2.7a shows that average energy of the electron fluence does not change

significantly with depth past a build-up region of up to 5 cm depth. It can be seen from Figure 2.7b that photon beam softening occurs for all four beams in the first few centimeters depth in a water phantom due to build-up of the low-energy photons scattered in the phantom and past this depth gradual hardening of the photon beam due to attenuation starts dominating, as observed by Cunningham et al⁵³ and Brahme and Andreo.³⁵ A second significant observation is that for the heavily filtered spectra, initial beam softening with depth is more pronounced than for lightly filtered spectra and beam hardening at greater depths is a more significant effect for soft spectra, increasing the average energy of the photon spectra by about 15 % between depths of 10 and 20 cm. From Table 2.13 and Figures 2.7a, 2.7b it can be seen that $\%dd(10)_x$ correlates well with the average energy of the electron fluence $\bar{E}_{e^-}$ on the central axis for different spectra ($\%dd(10)_x$ increases with $\bar{E}_{e^-}$), but TPR_{10}^{20} does not increase with $\bar{E}_{e^-}$. In contrast, TPR_{10}^{20} correlates well with average energy of the photon fluence spectra for the depth bin between 10 and 11 cm on a central axis as well as with average energy of the incident beam which can be approximated by the $\bar{E}_\gamma$ for the first depth bin from 0 to 1 cm (TPR_{10}^{20} increase with $\bar{E}_\gamma$).

Table 2.13: Energy of the electron, $\bar{E}_{e^-}$, and photon, $\bar{E}_\gamma$, fluence spectra averaged over the depth bin between 10 and 11 cm, on the central axis ($r=0-2$. cm, CA) and off-axis ($r=2-15$ cm, OA) in the water phantom, shown in Figure 2.6. Calculated using FLURZnrc. Values of $\bar{E}_{e^-}$ and $\bar{E}_\gamma$ are given with their relative standard deviations in parenthesis. Values of $\%dd(10)_x$ and TPR_{10}^{20} are taken from Table 2.4 and 2.9, respectively.

Spectrum label, NAP	$\%dd(10)_x$ %	TPR_{10}^{20}	$\bar{E}_{e^-}$ (CA) MeV	$\bar{E}_{e^-}$ (OA) MeV	$\bar{E}_\gamma$ (CA) MeV	$\bar{E}_\gamma$ (OA) MeV
NRC soft 20 MV	79.7	0.756	2.68 (0.8%)	2.639 (0.2%)	2.565 (0.1%)	1.886 (0.0%)
NRC hard 20 MV	82.0	0.782	2.893 (0.4%)	2.864 (0.2%)	3.790 (0.1%)	2.930 (0.1%)
NRC soft 25 MV	83.9	0.773	3.220 (0.5%)	3.215 (0.3%)	3.231 (0.2%)	2.390 (0.1%)
NRC hard 25 MV	86.8	0.805	3.527 (0.3%)	3.477 (0.1%)	4.883 (0.1%)	3.812 (0.0%)

Figure 2.7: Energy of the electron (a) and photon (b) spectra averaged over the depth bins on the central axis ($r=0-2$ cm) in a water phantom, shown in Figure 2.6, vs. depth in a phantom, calculated using FLURZnrc. Above each curve $\%dd(10)_x$ values calculated in the present work, Table 2.4, and TPR_{10}^{20} values calculated by Yang et al,⁴⁹ Table 2.9, are shown for the relevant beams.

Chapter 3

Results and Discussion

3.1 $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$ vs. TPR_{10}^{20}

Figure 3.1 presents calculated stopping-power ratios $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$ versus TPR_{10}^{20} for the 12 sets of photon beam spectra studied. The spread in $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$ confirms the previously reported results^{24,25,31} giving differences in $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$ values of up to 1 % for beams with the same value of TPR_{10}^{20} .

The first new result of the present study is also shown in Figure 3.1, which demonstrates a one-to-one relationship between stopping-power ratio and TPR_{10}^{20} for all clinical beams studied, except for the MM50 racetrack machines. This was shown for the first time for such a big variety of photon spectra from modern commercial linear accelerators, including detailed models of Varian, Siemens and Electra machines recently modelled by the Sheikh-Bagheri and Rogers⁴⁶ and older set of Varian accelerator beams from Mohan et al,²⁶ (for the details of their Monte Carlo simulations of commercial linacs see Appendix A and the original papers). From an analysis

of the Figure 3.1, it can be seen that not only are the photon beams produced by commercial clinical accelerators all on the same curve, but so are other “clinic-like” beams, viz. those NPL and NRC standard beams with additional “hard” or “heavy” filtration added past the target. It confirms the conjectures of Andreo³³ that (a) all “clinic-like” beams behave in the same way; and (b) it is possible to have “non-clinical” beams at standards laboratories which can be considered to be “clinic-like” in the sense that TPR_{10}^{20} can be an adequate beam quality specifier when choosing stopping-power ratios $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$.

One approach to decide if a beam of interest is clinic-like or not, is to repeat the calculations of the present work, viz. calculate photon spectra at the surface of the phantom, calculate stopping-power ratios $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$ using these spectra and calculate (or measure) the values of TPR_{10}^{20} to see if the beam of interest lies on the “clinic-like” curve in Figure 3.1. Although very precise, this method might not be very practical in a clinical environment. However it would be useful for a standards laboratory when choosing the flattening filter thickness and material to create a “clinic-like” photon beam. Another possible solution is suggested below in Section 3.3 using TPR_{10}^{20} and $\%dd(10)_x$.

It also can be seen from Figure 3.1, that all non-filtered beams, except those from racetrack machines, lie on the second curve shifted down to the lower values of $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$ for the same values of TPR_{10}^{20} .

Figure 3.1: Spencer-Attix water to air stopping-power ratios calculated using the DDSPR code (based on the ICRU 37 stopping powers) versus TPR_{10}^{20} for 12 sets of beams. All heavily filtered beams, i.e. clinical and “clinic-like”, are shown as closed symbols. Beams referred to as “NRC m Al”, etc., are measured⁵⁰ thick target beams where “Al”, etc., refers to the material of the target, and “+ Al” means additional aluminum filtration.

3.2 $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$ vs. $\%dd(10)_x$

In Figure 3.2 values of $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$ calculated using DDSPR are presented versus $\%dd(10)_x$ calculated using the BEAM Monte Carlo system, as described in Section 2.4.1. This Figure confirms the unique relationship which exists between stopping-power ratios and $\%dd(10)_x$ for all beams studied, including the MM50 racetrack 30 and 50 MV beams.^{25,27} The solid line is a linear fit to all the data, except the 4 MV NPL lightly filtered beam ($\%dd(10)_x=60.1(1)\%$). The fit has an rms deviation of 0.0013 and a maximum deviation 0.0027 which corresponds to 0.26% in the value of $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$ for the 30 MV NRC hard beam. This confirms previously reported results^{25,27} but for a broader range of beams.

The relationship between stopping-power ratio and $\%dd(10)_x$ obtained by a linear fit is:

$$\left(\frac{\bar{L}}{\rho}\right)_{air}^w = 1.2674 - 0.002216\%dd(10)_x \quad (3.1)$$

Equation 3.1 confirms the original relationship between $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$ and $\%dd(10)_x$ obtained by Konsunen and Rogers,²⁵ which almost coincides with the present fit, especially for low energy beams (see Figure 3.2). The linear fit from Rogers and Yang,²⁷ which is what is used in the TG-51 protocol, is also given for comparison in Figure 3.2. The maximum difference between the present fit's values of $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$ and the values of $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$ from Konsunen and Rogers²⁵ fit at high energies is about 0.05%. The maximum difference between the present fit's values of $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$ and the values of $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$ from Rogers and Yang²⁷ fit at low energies is about 0.2%. It confirms the calculational approach for obtaining water to air stopping-power ratios for k_Q calculation adopted in TG-51 dosimetry protocol.

Figure 3.2: Spencer-Attix water to air stopping-power ratios calculated using DDSPR code (based on the ICRU 37 stopping powers) versus $\%dd(10)_x$ for 12 sets of beams. All heavily filtered beams, i.e. clinical and “clinic-like”, are shown as closed symbols. Beams referred to as “NRC m Al”, etc., are measured⁵⁰ thick target beams where “Al”, etc., refers to the material of the target, and “+ Al” means additional aluminum filtration. The fit is given by Eq. 3.1 with an rms deviation 0.0013 and a maximum deviation 0.0029. The thin long-dashed line is the fit obtained by Kon-sunen and Rogers,²⁵ which almost coincides with the fit of the present work. The thick dashed line is the linear fit from Rogers and Yang.²⁷

Considering that the restricted stopping-power ratio water to air is a slowly decreasing function of electron energy between 100 keV and 50 MeV due to the difference of the density effect on the stopping powers of water and air, it would be plausible to suggest that a good beam quality specifier for choosing stopping-power ratios for dosimetry purposes should strongly correlate with the average energy of the electron fluence spectrum in the water irradiated by the bremsstrahlung photon beam of interest. As was found in the FLURZnrc calculations for the 20 and 25 MV soft and hard beams of the NRC linac, (see Section 2.5, page 44), the mean energy of the electron spectra in phantom correlates well with $\%dd(10)_x$ but not TPR_{10}^{20} . The value of $\%dd(10)_x$ is related to the depth of the maximum dose d_{max} , which in turn is related to the electron range in the water for electrons set in motion in the first layers of water and to the average energy of the electron fluence. In contrast, as shown above, the TPR_{10}^{20} value, which reflects the specifics of the attenuation of the photon beam in a water phantom between 10 and 20 cm depth, correlates well with the average energy of the incident photon spectrum.

3.3 TPR_{10}^{20} vs $\%dd(10)_x$

In Figure 3.3 TPR_{10}^{20} beam quality specifiers are shown versus $\%dd(10)_x$ for the same 12 sets of calculated spectra as in Fig. 3.1 and 3.2. In addition, 7 more sets of measured pairs of beam quality specifiers which have been published elsewhere^{31,47,54-57} are also shown in Figure 3.3.

Values of $\%dd(10)_x$ and TPR_{10}^{20} from Palmans et al⁵⁶ were measured for a field size of 12x12 cm² instead of 10x10 cm². Using their BEAM input files, photon spectra

Figure 3.3: Values of TPR_{10}^{20} versus $\%dd(10)_x$ for the same 12 sets of calculated spectra as in Fig. 3.1 and 3.2, and 7 more sets of measured beam quality specifiers are included.^{31,47,54-57} The line is a cubic fit to the clinic-like beams shown as closed symbols (except for the MM50 beams). The fit to a third-order polynomial is given by Eq. 3.2 with an rms deviation 0.0043 and a maximum deviation 0.010.

on a central axis have been calculated and used as input to the DDSPR code to obtain a rough estimate of the $\%dd(10)_x$ and TPR_{10}^{20} values for 10×10 cm² fields. The pairs of $\%dd(10)_x$ and TPR_{10}^{20} values are shown in Figure 3.3 as the “Gent, DDSPR” data set and these are not as unusual as the raw data of Palmans et al.

All clinical data (calculated in the present work based on the spectra of Sheikh-Bagheri and Rogers,⁴⁶ Mohan et al²⁶ and the MM50 racetrack spectra; and measured data from Ding et al,⁵⁴ Huq and Andreo,⁵⁵ Khan⁵⁷) and “clinic-like” spectra (NPL heavily filtered spectra both as calculated in the present work and by Walters and Rogers, based on values measured at NPL,⁴⁷ and the NRC hard spectra) are shown as closed symbols. The line is a least squares fit to a third-order polynomial of all

clinical and “clinic-like” data points in Figure 3.3 and 3.4, except the MM50 racetrack beams. The fit has an rms deviation of 0.0043 (fractional rms deviation 0.62%) and

Figure 3.4: Values of TPR_{10}^{20} versus $\%dd(10)_x$ for the same 8 sets of clinical and “clinic-like” beams shown as closed symbols in Figure 3.3 (except for the MM50 beams). The fit to a third-order polynomial is given by Eq. 3.2 and is the same as in Figure 3.3.

a maximum deviation 0.010 (1.4%).

The relationship between TPR_{10}^{20} and $\%dd(10)_x$ given by the least squares fit to the third-order polynomial shown in Figure 3.3 is:

$$TPR_{10}^{20} = 6.289 \cdot 10^{-7} (\%dd(10)_x)^3 - 3.321 \cdot 10^{-4} (\%dd(10)_x)^2 + 0.0466 (\%dd(10)_x) - 1.152 \quad (3.2)$$

The AAPM’s TG-51 protocol⁵ gives a general formula, first obtained by Rogers,¹² which can be used to derive $\%dd(10)_x$, the percentage depth-dose at 10 cm for the *photon* component of the depth dose curve, from $\%dd(10)$, the percentage

depth-dose at 10 cm for the total depth-dose curve:

$$\%dd(10)_x = 1.267\%dd(10) - 20.0 \quad (3.3)$$

where $\%dd(10)$ is measured for higher energy beams (for $75\% < \%dd(10) \leq 89\%$). For low-energy beams, i.e., for energies below 10 MV with $\%dd(10) \leq 75\%$, $\%dd(10) = \%dd(10)_x$. Assuming that the relation established by Equation 3.3 holds for higher energy beams, Equation 3.2 can be rewritten as:

$$TPR_{10}^{20} = 1.279 \cdot 10^{-6}(\%dd(10))^3 - 5.937 \cdot 10^{-4}(\%dd(10))^2 + 0.0769(\%dd(10)) - 2.223 \quad (3.4)$$

where $\%dd(10)$ is the total percentage depth-dose at 10 cm measured for a field size of $10 \times 10 \text{ cm}^2$ at the phantom surface at an SSD of 100 cm.

Figure 3.3 and Equations 3.2 and 3.4 give an easily used criterion for establishing if a given beam is “clinic-like” or not, i.e. for establishing if TPR_{10}^{20} is a good beam quality specifier or not. For higher energy beams one can measure TPR_{10}^{20} and $\%dd(10)_x$, using a lead foil as described in the AAPM’s TG-51 protocol⁵ to see if they lie on the “clinic-like” curve in Figure 3.3 or 3.4 (i.e. if they satisfy Equation 3.3). For measured values of $\%dd(10)$ the same can be done directly with $\%dd(10)$ for lower energy beams and for a high energy beams one can check whether an Equation 3.4 is satisfied.

Another possible use of the relationship between the TPR_{10}^{20} and $\%dd(10)_x$ established by Equation 3.2 is to determine the effective “clinical” TPR_{10}^{20} for the standards laboratory calibration beam if it does not lie on a curve in Figure 3.3 or 3.4. Having measured a value of $\%dd(10)_x$, one can calculate effective clinical TPR_{10}^{20} values using Equation 3.2. Table 3.1 gives effective clinical TPR_{10}^{20} values for the standard beams at NRC. It is clear that these beams are not “clinic-like” if one is

using TPR_{10}^{20} as a beam quality specifier.

Table 3.1: Values of effective clinical TPR_{10}^{20} of the NRC standard beams, calculated using Equation 3.2 and $\%dd(10)_x$ values measured by Seuntjens et al.³¹ Measured values of TPR_{10}^{20} are presented for comparison.

Energy, MV	measured $\%dd(10)_x$	measured TPR_{10}^{20}	effective TPR_{10}^{20}
10	69.6(2)	0.682(1)	0.698
20	80.5(2)	0.758(1)	0.780
30	88.4(2)	0.794(1)	0.810

The inverse to the relationship in Equation 3.2 between $\%dd(10)_x$ and TPR_{10}^{20} can be established in the same way as Equation 3.2. The relationship between $\%dd(10)_x$ and TPR_{10}^{20} (rms deviation 0.611 (fractional rms deviation 0.79%) and a maximum deviation 1.65 (1.8%)) is:

$$\%dd(10)_x = 1905 (TPR_{10}^{20})^3 - 3632 (TPR_{10}^{20})^2 + 2384.5 TPR_{10}^{20} - 473.4 \quad (3.5)$$

In a clinical situation, Equations 3.2 and 3.5 can be used when transferring to the new TG-51 protocol from the TG-21 dosimetry protocol. Using newly measured values of $\%dd(10)_x$ and Equation 3.2, one can calculate TPR_{10}^{20} values and confirm that it gives the same TPR_{10}^{20} as previously used in the TG-21 protocol. Alternatively, values of $\%dd(10)_x$ can be calculated using Equation 3.5 and measured values of TPR_{10}^{20} .

Chapter 4

Conclusions

Based on the Monte Carlo calculations for 12 sets of bremsstrahlung photon spectra, it can be concluded that $\%dd(10)_x$ is a unique beam quality specifier for all photon beams studied. This confirms previously reported results^{12,20,25,27,31} but for a broader range of beams and with more detailed calculations of $\%dd(10)_x$.

For all of the 14 standard clinical beams studied, including detailed models of Varian, Siemens and Elekta machines, TPR_{10}^{20} is an adequate beam quality specifier, but it is not a good beam quality specifier for the MM50 beams nor many other beams in standards laboratories.

With caution, TPR_{10}^{20} can be used as a beam quality specifier for a family of clinical and “clinic-like” spectra. The relationship, derived in the present work, between TPR_{10}^{20} and $\%dd(10)_x$ for all “clinic-like” spectra, shown on Figure 3.3 and given by Equation 3.2 (or Equation 3.4 for $\%dd(10)$), gives an easily used criterion for establishing if a given beam is clinic-like or not, i.e. for establishing if TPR_{10}^{20} is a good beam quality specifier or not.

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Appendix A

Photon spectra from ENSRC distribution

Many of the spectra described in this Appendix have been distributed as part of the EGS4 code system for Monte Carlo transport.³⁸ The spectra are distributed in the ENSRC format which is read by a variety of EGS4 and EGSnrc user-codes⁵² (eg DOSRZnrc, FLURZnrc, etc). Some of the spectra (Mohan et al,²⁶ racetrack and NRC measured spectra) have been part of the NRC collection for years , while the others have been collected and converted to the ENSRC format during the present calculations. The recently collected spectra and photon spectra from the NRC standard beams and NRC soft and hard filtered beams calculated as described in Section 2.3.1, have become a part of the NRC photon spectra catalogue⁵⁸ which soon will be available on-line at the same location as EGSnrc:

<http://www.irs.inms.nrc.ca/inms/irs/EGSnrc/EGSnrc.html>

A.1 Varian spectra calculated by Mohan et al

Various accelerators manufactured by the Varian Corporation, viz. the Clinac-4 (4 MV), -6 (6 MV), -18 (10 MV), -20 (15 MV), and -2500 (24 MV) were modelled by Mohan et al²⁶ using EGS Version 3.⁵⁹ Incident electron beams from the accelerator were assumed to be monoenergetic with no spatial spread. The photon spectra were verified by calculating tissue-maximum ratios (TMR's) in water using the energy spectra on the central axis and at a distance of 12 cm from the central axis and comparing them with TMR's measured in polystyrene for a field size of 10x10 cm² defined at the isocenter and 12 cm laterally from the isocenter. Measured and calculated TMR's on the central axis agree within 1 % except for the 10 MV photon beam for which agreement at the depths beyond the depth of the maximum dose is somewhat worse. Half-value layers of water calculated using 4MV and 6MV spectra were shown to agree within 3 % with measured data.

During preparation of the present catalogue it has been discovered that the energy structure of the spectra referred to as the 15 MV and 10 MV Mohan spectra, and distributed along with standard energy source spectra set for EGS4 NRC user codes, were altered compared to the original spectra. Those spectra have been re-digitalized from the original paper using WinDIG software (<http://www.unige.ch/cpb/windig.html>). Beam quality specifiers and stopping power ratios in the present work have been calculated using the 15 MV and 10 MV corrected spectra.

A.2 Clinical spectra calculated by Sheikh-Bagheri and Rogers

Elekta SL25 6MV and 25 MV beams; Siemens KD 6 MV and 18 MV; Varian Clinac-4 MV and Clinac 2100C/2300C 6 MV, 10 MV, 15 MV and 18 MV photon beams have been simulated at NRC using the BEAM Monte Carlo system.^{36,37,46} The simulations have been benchmarked against compiled measured data (off-axis factors and relative depth-dose values) of task group 46 of the AAPM;⁶⁰ for the Elekta machines to the data published by Palta et al⁶¹ and for the Siemens 18 MV beam to the relative depth-dose data measured by Dr. A. Siochi⁴⁶ of Siemens. After adjusting the incident electron energy and spatial distributions, calculated and measured depth-dose data agree within 1% (local dose), for statistics of about 1% (1σ level), at all depths past the depth of the maximum dose for all beams, except for the 6 MV Varian beam for which agreement is somewhat worse. Good agreement for the off-axis ratios was also obtained. To obtain spectra for the present work, BEAM input files have been used with a set of incident electron beam parameters from Sheikh-Bagheri.³⁶ This set is slightly different from that given in the latest publication.⁴⁶ These differences have been shown not to make any significant change for the present calculations in the photon spectral distributions on the central axis for the field size $10\times 10\text{ cm}^2$ at 100 cm SSD.

Spectra have been calculated by Rogers⁵⁸ using Sheikh-Bagheri and Rogers input files for the BEAM simulation of the above accelerators. Phase space files have been collected at 100 cm distance from the source for a $10\times 10\text{ cm}^2$ field on the central axis and spectra have been obtained using the BEAMDP computer code.⁴¹ Typical statistical uncertainties for the fluence per energy bin are 0.5 % at the maxima of the

spectra and 1.-1.5 % elsewhere except for energy bins close to the maximum energy.

A.3 Racetrack Microtron calculated spectra

30- and 50-MV beams are from the Scanditronix 50-MV racetrack microtron in which bremsstrahlung beams from a thick tungsten/copper target are swept across the field to achieve flatness. Spectra have been calculated by Konsunen and Rogers²⁵ using the code ACCEL which is a minor modification of the FLURZ NRC user code based on EGS4 Monte Carlo system.³⁸ ACCEL models cylindrically symmetric accelerator heads. The flattening filters were modelled as a stacked set of cylinders. The machine specifications were for the Memorial Sloan-Kettering Cancer Center's MM50.

A.4 NPL calculated spectra

Photon beams with nominal energy from 4 MV to 19 MV for the linear accelerator of the National Physical Laboratory, UK (NPL) have been modelled using BEAM.⁴⁷ Two sets of the beams ("heavy" and "light") differ by the amount of additional 1-10 cm of aluminum filtration added below the lower collimator and up to 4 cm of aluminum attached to the back of the target. Values of %dd(10) and TPR₁₀²⁰ calculated from BEAM depth-dose curves have been compared to those measured at NPL. Values of %dd(10) were found within 2.5% of measured values (rms deviation = 1%). The 4 MV beam in particular differed from measurements but most other beams agreed much better. Calculated values of TPR₁₀²⁰ were within 1% of measurement (rms deviation = 0.4%).

Photon spectra have been calculated in the present work using the phase space

files of Walters and Rogers,⁴⁷ collected at 118-120 cm SSD for a field size of 10x10 cm² defined at 118-120 cm SSD, and using the BEAMDP code.

A.5 Thick target bremsstrahlung spectra measured at NRC

Bremsstrahlung spectra from thick targets of Al, Pb and Be have been measured absolutely^{50,62} in the sense of number of photons which emerge from the target into a given solid angle along the beam axis per electron incident on the target for electrons of 10, 15, 20, 25 and 30 MeV incident energy. The spectra have a 220 keV low-energy cutoff. The targets were cylinders with nominal thicknesses of 110% of the electron CSDA range. The spectrometer was a 20.3-cm-diameter by 25.4-cm-long cylindrical NaI detector. Measured spectra were corrected for pile-up, background, detector response, detector efficiency, attenuation in materials between the target and detector and the collimator effect. The integrated bremsstrahlung yield was obtained with a measurement uncertainty of $\pm 5\%$. Typical uncertainties per energy bin were from 2 to 5 % (systematic uncertainties in spectral measurements and uncertainties in the beam current are not included).

Measured spectra have been compared to spectra calculated using the EGS4 Monte Carlo system.³⁸ The measured spectral shapes agreed with the calculations for all targets for all five energies studied. For a given target, the ratios of the measured bremsstrahlung yields to the calculated bremsstrahlung yields were generally found to be independent of electron energy within the range of relative uncertainties of these ratios of $\pm 4\%$ to $\pm 6\%$. Those results verified the use of EGS4 for absolute calculation

of the bremsstrahlung yield in the forward direction.

The pair of spectra referred to as “NRC measured Al + Al” have been obtained by Konsunen and Rogers²⁵ starting from the measured 10- and 20-MV thick aluminum target spectra which were analytically filtered by an additional 14 cm of aluminum.