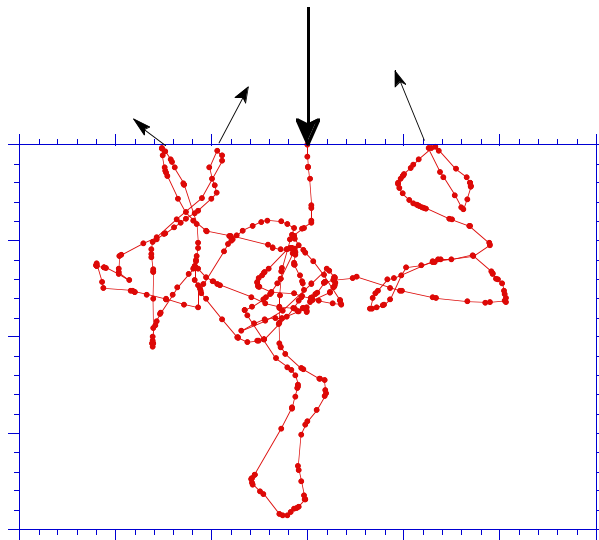


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# Monte Carlo Modeling of Light Transport in Multi-layered Tissues in Standard C

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<http://biomed.tamu.edu/~lw> or <http://ece.ogi.edu/omlc>

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Citation of the following references when reporting results computed with this software package are appreciated:

1. L.-H. Wang, S. L. Jacques, and L.-Q. Zheng, "MCML - Monte Carlo modeling of photon transport in multi-layered tissues," *Computer Methods and Programs in Biomedicine* **47**, 131-146 (1995).
2. L.-H. Wang, S. L. Jacques, and L.-Q. Zheng, "CONV - Convolution for responses to a finite diameter photon beam incident on multi-layered tissues," *Computer Methods and Programs in Biomedicine* **54**, 141-150 (1997).

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## **Abstract**

A Monte Carlo model of steady-state light transport in multi-layered tissue (mcml) and the corresponding convolution program (conv) have been coded in ANSI Standard C. The programs can therefore be executed on a variety of computers. Dynamic data allocation is used for mcml, hence the number of tissue layers and the number of grid elements of the grid system can be varied by users at run time as long as the total amount of memory does not exceed what the system allows. The principle and the implementation details of the model, and the instructions for using mcml and conv are presented here. We have verified some of the mcml and conv computation results with those of other theories or other investigators.

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## Table of Contents

ABSTRACT.....	II
ACKNOWLEDGMENT.....	III
<i>Table of Contents</i> .....	<i>iv</i>
0. INTRODUCTION.....	1
<b>PART I. DESCRIPTION OF MONTE CARLO SIMULATION.....</b>	<b>4</b>
1. THE PROBLEM AND COORDINATE SYSTEMS.....	4
2. SAMPLING RANDOM VARIABLES.....	7
3. RULES FOR PHOTON PROPAGATION.....	10
3.1 <i>Launching a photon packet</i> .....	10
3.2 <i>Photon's step size</i> .....	11
3.3 <i>Moving the photon packet</i> .....	13
3.4 <i>Photon absorption</i> .....	14
3.5 <i>Photon scattering</i> .....	14
3.6 <i>Reflection or transmission at boundary</i> .....	16
3.7 <i>Reflection or transmission at interface</i> .....	18
3.8 <i>Photon termination</i> .....	19
4. SCORED PHYSICAL QUANTITIES.....	20
4.1 <i>Reflectance and transmittance</i> .....	20
4.2 <i>Internal photon distribution</i> .....	22
4.3 <i>Issues regarding grid system</i> .....	25
5. PROGRAMMING MCML.....	30
5.1 <i>Programming rules and conventions</i> .....	30
5.2 <i>Several constants</i> .....	31
5.3 <i>Data structures and dynamic allocations</i> .....	32
5.4 <i>Flowchart of photon tracing</i> .....	36
5.5 <i>Flow of the program mcml</i> .....	39
5.6 <i>Multiple simulations</i> .....	41
5.7 <i>Timing profile of the program</i> .....	42
6. COMPUTATION RESULTS OF MCML AND VERIFICATION.....	45
6.1 <i>Total diffuse reflectance and total transmittance</i> .....	45
6.2 <i>Angularly resolved diffuse reflectance and transmittance</i> .....	46
6.3 <i>Radially resolved diffuse reflectance</i> .....	47
6.4 <i>Depth resolved internal fluence</i> .....	48

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6.5	<i>Computation times vs optical properties</i> .....	50
6.6	<i>Scored Physical Quantities of Multi-layered Tissues</i> .....	60
7.	CONVOLUTION FOR PHOTON BEAMS OF FINITE SIZE.....	65
7.1	<i>Principles of convolution</i> .....	65
7.2	<i>Convolution over Gaussian beams</i> .....	69
7.3	<i>Convolution over circularly flat beams</i> .....	70
7.4	<i>Numerical solution to the convolution</i> .....	71
7.5	<i>Computation results of conv and verification</i> .....	78
<b>PART II. USER MANUAL</b> .....		<b>85</b>
8.	INSTALLING MCML AND CONV.....	85
8.1	<i>Installing on Sun workstations</i> .....	85
8.2	<i>Installing on IBM PC compatibles</i> .....	86
8.3	<i>Installing on Macintoshes</i> .....	86
8.4	<i>Installing by Electronic Mail</i> .....	87
9.	INSTRUCTIONS FOR MCML.....	89
9.1	<i>File of input data</i> .....	89
9.2	<i>Execution</i> .....	91
9.3	<i>File of output data</i> .....	93
9.4	<i>Subset of output data</i> .....	94
9.5	<i>Bugs of mcml</i> .....	95
10.	INSTRUCTIONS FOR CONV.....	97
10.1	<i>Start conv</i> .....	97
10.2	<i>Main menu of conv</i> .....	97
10.3	<i>Command "i" of conv</i> .....	98
10.4	<i>Command "b" of conv</i> .....	98
10.5	<i>Command "r" of conv</i> .....	99
10.6	<i>Command "e" of conv</i> .....	99
10.7	<i>Command "oo" of conv</i> .....	100
10.8	<i>Command "oc" of conv</i> .....	101
10.9	<i>Command "co" of conv</i> .....	103
10.10	<i>Command "cc" of conv</i> .....	104
10.11	<i>Command "so" of conv</i> .....	105
10.12	<i>Command "sc" of conv</i> .....	106
10.13	<i>Command "q" of conv</i> .....	107
10.14	<i>Bugs of conv</i> .....	107

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11. HOW TO MODIFY MCML .....	109
<b>APPENDICES.....</b>	<b>112</b>
APPENDIX A. CFLOW OUTPUT OF THE PROGRAM MCML.....	112
APPENDIX B. SOURCE CODE OF THE PROGRAM MCML .....	116
<i>B.1 mcml.h</i> .....	116
<i>B.2 mcmlmain.c</i> .....	120
<i>B.3 mcmlio.c</i> .....	124
<i>B.4 mcmlgo.c</i> .....	144
<i>B.5 mcmlnr.c</i> .....	157
APPENDIX C. MAKEFILE FOR THE PROGRAM MCML.....	159
APPENDIX D. A TEMPLATE OF MCML INPUT DATA FILE.....	160
APPENDIX E. A SAMPLE OUTPUT DATA FILE OF MCML .....	161
APPENDIX F. SEVERAL C SHELL SCRIPTS .....	163
<i>F.1 conv.bat for batch processing conv</i> .....	163
<i>F.2 p1 for pasting files of 1D arrays</i> .....	164
APPENDIX G. WHERE TO GET THE PROGRAMS MCML AND CONV.....	166
APPENDIX H. FUTURE DEVELOPMENTS OF THE PACKAGE .....	167
<b>REFERENCES.....</b>	<b>169</b>
<b>INDEX.....</b>	<b>172</b>

## 0. Introduction

Monte Carlo simulation has been used to solve a variety of physical problems. However, there is no succinct well-established definition. We would like to adopt the definition by Lux *et al.* (1991). In all applications of the Monte Carlo method, a stochastic model is constructed in which the expected value of a certain random variable (or of a combination of several variables) is equivalent to the value of a physical quantity to be determined. This expected value is then estimated by the average of multiple independent samples representing the random variable introduced above. For the construction of the series of independent samples, random numbers following the distribution of the variable to be estimated are used.

Monte Carlo simulations of photon propagation offer a flexible yet rigorous approach toward photon transport in turbid tissues. The method describes local rules of photon propagation that are expressed, in the simplest case, as probability distributions that describe the step size of photon movement between sites of photon-tissue interaction, and the angles of deflection in a photon's trajectory when a scattering event occurs. The simulation can score multiple physical quantities simultaneously. However, the method is statistical in nature and relies on calculating the propagation of a large number of photons by the computer. As a result, this method requires a large amount of computation time.

The number of photons required depends largely on the question being asked, the precision needed, and the spatial resolution desired. For example, to simply learn the total diffuse reflectance from a tissue of specified optical properties, typically about 3,000 photons can yield a useful result. To map the spatial distribution of photons,  $\phi(r, z)$ , in a cylindrically symmetric problem, at least 10,000 photons are usually required to yield an acceptable answer. To map spatial distributions in a more complex three-dimensional problem such as a finite diameter beam irradiating a tissue with a buried blood vessel, the required photons may exceed 100,000. The point to be remembered in these introductory remarks is that Monte Carlo simulations are rigorous, but necessarily statistical and therefore require significant computation time to achieve precision and resolution. Nevertheless, the flexibility of the method makes Monte Carlo modeling a powerful tool.

Another aspect of the Monte Carlo simulations presented in this paper deserves emphasis. The simulations described here do not treat the photon as a wave phenomenon, and ignore such features as phase and polarization. The motivation for these simulations is

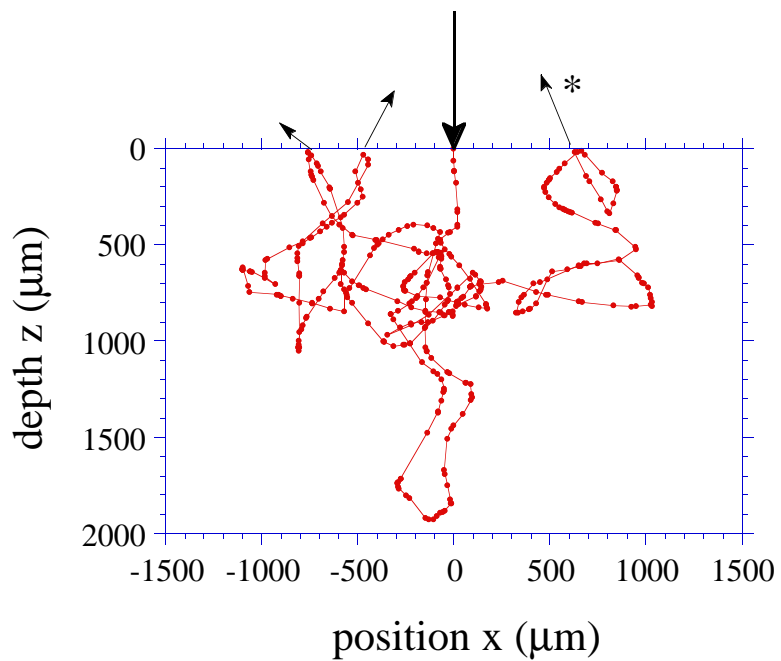


to predict radiant energy transport in turbid tissues. The photons are multiply scattered by most tissues, therefore phase and polarization are quickly randomized, and play little role in energy transport. Although the Monte Carlo simulations may be capable of bookkeeping phase and polarization and treating wave phenomena statistically, this manual will not consider these issues.

The Monte Carlo simulations are based on macroscopic optical properties that are assumed to extend uniformly over small units of tissue volume. Mean free paths between photon-tissue interaction sites typically range from 10-1000  $\mu\text{m}$ , and 100  $\mu\text{m}$  is a very typical value in the visible spectrum (Cheong *et al.*, 1990). The simulations do not treat the details of radiant energy distribution within cells, for example.

As a simple example of the Monte Carlo simulation. We would like to present a typical trajectory of a single photon packet in Fig. 0.1. Each step between photon positions (dots) is variable and equals  $-\ln(\xi)/(\mu_a + \mu_s)$  where  $\xi$  is a random number and  $\mu_a$  and  $\mu_s$  are the absorption and scattering coefficients, respectively (in this example,  $\mu_a = 0.5 \text{ cm}^{-1}$ ,  $\mu_s = 15 \text{ cm}^{-1}$ ,  $g = 0.90$ ). The value  $g$  is the anisotropy of scattering. The weight of the photon is decreased from an initial value of 1 as it moves through the tissue, and equals  $a^n$  after  $n$  steps, where  $a$  is the albedo ( $a = \mu_s/(\mu_a + \mu_s)$ ). When the photon strikes the surface, a fraction of the photon weight escapes as reflectance and the remaining weight is internally reflected and continues to propagate. Eventually, the photon weight drops below a threshold level and the simulation for that photon is terminated. In this example, termination occurred when the last significant fraction of remaining photon weight escaped at the surface at the position indicated by the asterisk (\*). Many photon trajectories ( $10^4$  to  $10^6$ ) are typically calculated to yield a statistical description of photon distribution in the medium.

This manual is roughly divided into two major parts. Part I describes the principles of Monte Carlo simulations of photon transport in tissues, how to realize the simulation in ANSI Standard C, and some computation results and verifications. Part II provides users detailed instructions of using `mcml` and modifying `mcml` to suit special need, where `mcml` stands for Monte Carlo simulations for multi-layered tissues. The appendices furnish the flow graph and the whole source code of `mcml`, and some other useful information.



**Figure 0.1.** The movement of one photon through a homogenous medium, as calculated by Monte Carlo simulation.

## **Part I. Description of Monte Carlo Simulation**

### **1. The Problem and Coordinate Systems**

The Monte Carlo simulation described in this paper deals with the transport of an infinitely narrow photon beam perpendicularly incident on a multi-layered tissue. Each layer is infinitely wide, and is described by the following parameters: the thickness, the refractive index, the absorption coefficient  $\mu_a$ , the scattering coefficient  $\mu_s$ , and the anisotropy factor  $g$ . The refractive indices of the top ambient medium (e.g., air) and bottom ambient medium (if exists) have to be given as well. Although the real tissue can never be infinitely wide, it can be so treated if it is much larger than the spatial extent of the photon distribution. The absorption coefficient  $\mu_a$  is defined as the probability of photon absorption per unit infinitesimal pathlength, and the scattering coefficient  $\mu_s$  is defined as the probability of photon scattering per unit infinitesimal pathlength. For the simplicity of notation, the total interaction coefficient  $\mu_t$ , which is the sum of the absorption coefficient  $\mu_a$  and the scattering coefficient  $\mu_s$ , is sometimes used. Correspondingly, the interaction coefficient means the probability of photon interaction per unit infinitesimal pathlength. The anisotropy  $g$  is the average of the cosine value of the deflection angle (see Section 3.5).

Photon absorption, fluence, reflectance and transmittance are the physical quantities to be simulated. The simulation propagates photons in three dimensions, records photon deposition,  $A(x, y, z)$ , ( $\text{J}/\text{cm}^3$  per J of delivered energy or  $\text{cm}^{-3}$ ) due to absorption in each grid element of a spatial array, and finally calculates fluence,  $\phi(x, y, z)$ , ( $\text{J}/\text{cm}^2$  per J of delivered energy or  $\text{cm}^{-2}$ ) by dividing deposition by the local absorption coefficient,  $\mu_a$  in  $\text{cm}^{-1}$ :  $\phi(x, y, z) = A(x, y, z)/\mu_a$ . Since the photon absorption and the photon fluence can be converted back and forth through the local absorption coefficient of the tissue, we only report the photon absorption in mcml (see Section 4.2 and Section 9.3). The photon fluence can be obtained by converting the photon absorption in another program conv. The simulation also records the escape of photons at the top (and bottom) surface as local reflectance (and transmittance) ( $\text{cm}^{-2}\text{sr}^{-1}$ ) (see Section 4.1).

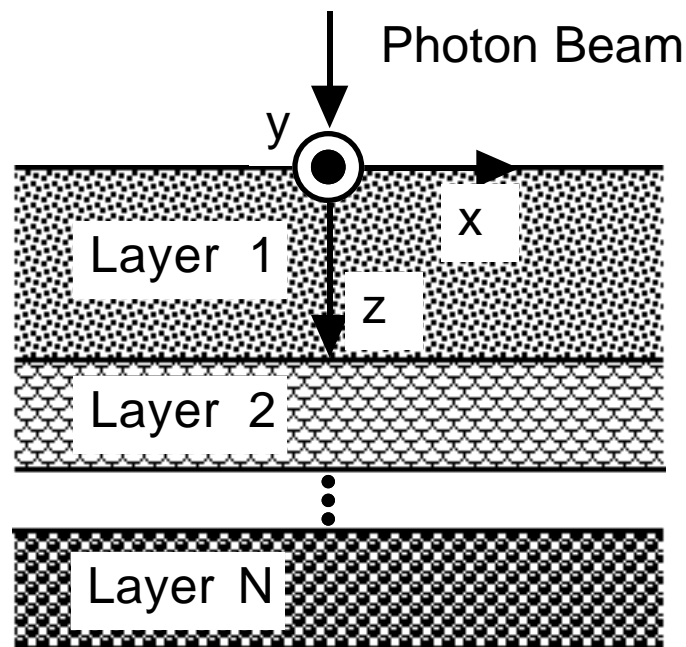
In this first version of mcml, we consider cylindrically symmetric tissue models. Therefore, we chose to record photon deposition in a two-dimensional array,  $A(r, z)$  although the photon propagation of this simulation is conducted in three-dimensions.

Three coordinate systems are used in the Monte Carlo simulation at the same time. A Cartesian coordinate system is used to trace photon packets. The origin of the coordinate

system is the photon incident point on the tissue surface, the  $z$ -axis is always the normal of the surface pointing toward the inside of the tissue, and the  $xy$ -plane is therefore on the tissue surface (Fig. 1.1). A cylindrical coordinate system is used to score internal photon absorption  $A(r, z)$ , where  $r$  and  $z$  are the radial and  $z$  axis coordinates of the cylindrical coordinate system respectively. The Cartesian coordinate system and the cylindrical coordinate system share the origin and the  $z$  axis. The  $r$  coordinate of the cylindrical coordinate system is also used for the diffuse reflectance and total transmittance. They are recorded on tissue surface in  $R_d(r, \alpha)$  and  $T_t(r, \alpha)$  respectively, where  $\alpha$  is the angle between the photon exiting direction and the normal ( $-z$  axis for reflectance and  $z$  axis for transmittance) to the tissue surfaces. A moving spherical coordinate system, whose  $z$  axis is aligned with the photon propagation direction dynamically, is used for sampling of the propagation direction change of a photon packet. In this spherical coordinate system, the deflection angle  $\theta$  and the azimuthal angle  $\psi$  due to scattering are first sampled. Then, the photon direction is updated in terms of the directional cosines in the Cartesian coordinate system (see Section 3.5).

For photon absorption, a two-dimensional homogeneous grid system is setup in  $z$  and  $r$  directions. The grid line separations are  $\Delta z$  and  $\Delta r$  in  $z$  and  $r$  directions respectively. The total numbers of grid elements in  $z$  and  $r$  directions are  $N_z$  and  $N_r$  respectively. For diffuse reflectance and transmittance, a two-dimensional homogeneous grid system is setup in  $r$  and  $\alpha$  directions. This grid system can share the  $r$  direction with the grid system for photon absorption. Therefore, we only need to set up an extra one dimensional grid system for the diffuse reflectance and transmittance in the  $\alpha$  direction. In our simulation, we always choose the range of  $\alpha$  to be  $[0, \pi/2]$ , i.e.,  $0 \leq \alpha \leq \pi/2$ . The total number of grid elements is  $N_\alpha$ . Therefore the grid line separation is  $\Delta\alpha = \pi/(2 N_\alpha)$ .

This is an appropriate time to mention that we always use cm as the basic unit of length throughout the simulation for consistency. For example, the thickness of each layer and the grid line separations in  $r$  and  $z$  directions are in cm. The absorption coefficient and scattering coefficient are in  $\text{cm}^{-1}$ .



**Fig. 1.1.** A schematic of the Cartesian coordinate system set up on multi-layered tissues. The y-axis points outward.

In some of the discussions, the arrays will simply be referenced by the location of the grid element, e.g.,  $(r, z)$  or  $(r, \alpha)$ , rather than by the indices of the grid element, although the indices are used in the program to reference array elements.

## 2. Sampling Random Variables

The Monte Carlo method, as its name implies ("throwing the dice"), relies on the random sampling of variables from well-defined probability distributions. Several books (Cashew *et al.*, 1959; Lux *et al.*, 1991; and Kalos *et al.*, 1986) provide good references for the principles of Monte Carlo modeling. Let us briefly review the method for sampling random variables in a Monte Carlo simulation.

Consider a random variable  $\chi$ , which is needed by the Monte Carlo simulation of photon propagation in tissue. This variable may be the variable step size a photon will take between photon-tissue interaction sites, or the angle of deflection a scattered photon may experience due to a scattering event. There is a probability density function that defines the distribution of  $\chi$  over the interval (a, b). The probability density function is normalized such that:

$$\int_a^b p(\chi) d\chi = 1 \quad (2.1)$$

To simulate propagation, we wish to be able to choose a value for  $\chi$  repeatedly and randomly based on a pseudo-random number generator. The computer provides a random variable,  $\xi$ , which is uniformly distributed over the interval (0, 1). The cumulative distribution function of this uniformly distributed random variable is:

$$F_{\xi}(\xi) = \begin{cases} 0 & \text{if } \xi \leq 0 \\ \xi & \text{if } 0 < \xi \leq 1 \\ 1 & \text{if } \xi > 1 \end{cases} \quad (2.2)$$

To sample a generally non-uniformly distributed function  $p(\chi)$ , we assume there exists a nondecreasing function  $\chi = f(\xi)$  (Kalos *et al.*, 1986), which maps  $\xi \in (0, 1)$  to  $\chi \in (a, b)$  (Fig. 2.1). The variable  $\chi$  and variable  $\xi$  then have a one-to-one mapping. This subsequently leads to the following equality of probabilities:

$$P\{f(0) < \chi \leq f(\xi_1)\} = P\{0 < \xi \leq \xi_1\} \quad (2.3a)$$

or

$$P\{a < \chi \leq \chi_1\} = P\{0 < \xi \leq \xi_1\} \quad (2.3b)$$

According to the definition of cumulative distribution functions, Eq. 2.3b can be changed to an equation of cumulative distribution functions:

$$F_{\chi}(\chi_1) = F_{\xi}(\xi_1) \quad (2.4)$$

Expanding the cumulative distribution function  $F_{\chi}(\chi_1)$  in terms of the corresponding probability density function for the left-hand side of Eq. 2.4 and employing Eq. 2.2 for the right-hand side, we convert Eq. 2.4 into:

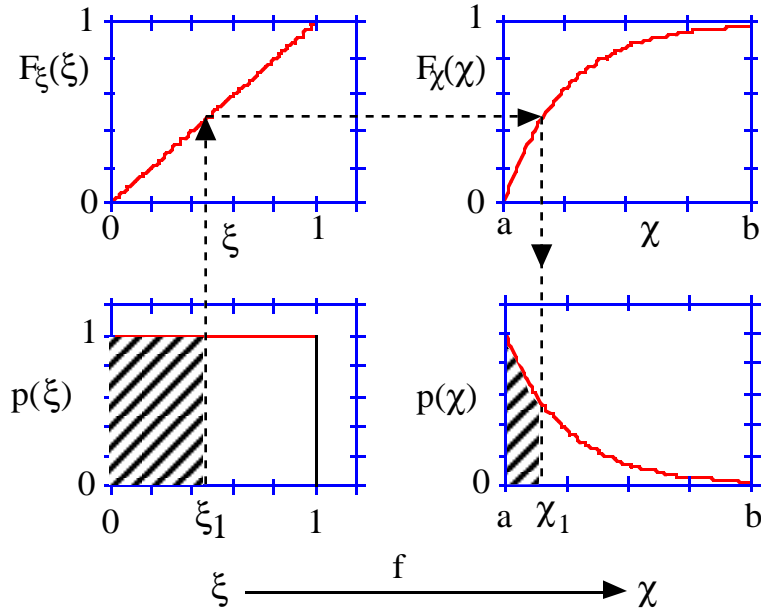
$$\int_a^{\chi_1} p(\chi) d\chi = \xi_1 \quad \text{for } \xi_1 \in (0, 1) \quad (2.5)$$

Eq. 2.5 is then used to solve for  $\chi_1$  to get the function  $f(\xi_1)$ . If the function  $\chi = f(\xi)$  is assumed nonincreasing, a similar derivation will lead to the counterpart of Eq. 2.5 as:

$$\int_a^{\chi_1} p(\chi) d\chi = 1 - \xi_1 \quad \text{for } \xi_1 \in (0, 1) \quad (2.6)$$

However, since  $(1 - \xi_1)$  and  $\xi_1$  have the same distribution, they can be interchanged. Therefore, Eq. 2.5 and Eq. 2.6 are equivalent. In the following chapter, Eq. 2.5 will be repeatedly invoked for sampling propagation variables.

The whole sampling process can be understood from Fig. 2.1. The key to the Monte Carlo selection of  $\chi$  using  $\xi$  is to equate the probability that  $\xi$  is in the interval  $[0, \xi_1]$  with the probability that  $\chi$  is in the interval  $[a, \chi_1]$ . In Fig. 2.1, we are equating the shaded area depicting the integral of  $p(\chi)$  over  $[0, \chi_1]$  with the shaded area depicting the integral  $p(\xi)$  over  $[0, \xi_1]$ . Keep in mind that the total areas under the curves  $p(\chi)$  and  $p(\xi)$  each equal unity, as is appropriate for probability density functions. The result is a one-to-one mapping between the upper boundaries  $\xi_1$  and  $\chi_1$  based on the equality of the shaded areas in Fig. 2. In other words, we have equated  $F_{\chi}(\chi_1)$  with  $F_{\xi}(\xi_1)$  (Eq. 2.4) which is equivalent to Eq. 2.5. The transformation process  $\chi_1 = f(\xi_1)$  is shown by the arrows. For each  $\xi_1$ , a  $\chi_1$  is chosen such that the cumulative distribution functions for  $\xi_1$  and  $\chi_1$  have the same value. Correspondingly, the hatched areas are equal. It can also be seen in Fig. 2.1 that the monotonic function  $f(\xi)$  always exists because both cumulative distribution functions of  $\xi$  and  $\chi$  are monotonic.



**Fig. 2.1.** Sampling a random variable  $\chi$  based on a uniformly distributed random variable  $\xi$ .

For example, consider the sampling of the step size for photon movement,  $s$ , which is to be discussed fully in Section 3.2. The probability density function is given:

$$p(s) = \mu_t \exp(-\mu_t s) \quad (2.7)$$

where interaction coefficient  $\mu_t$  equals  $\mu_a + \mu_s$ . Using this function in Eq. 2.5 yields an expression for a sampled value,  $s_1$ , based on the random number  $\xi$ :

$$\xi = \int_0^{s_1} p(s) ds = \int_0^{s_1} \mu_t \exp(-\mu_t s) ds = 1 - \exp(-\mu_t s_1) \quad (2.8)$$

Solving for the value  $s_1$ :

$$s_1 = \frac{-\ln(1 - \xi)}{\mu_t} \quad (2.9a)$$

As was explained in Eq. 2.6, the above expression is equivalent to:

$$s_1 = \frac{-\ln(\xi)}{\mu_t} \quad (2.9b)$$



### 3. Rules for Photon Propagation

This chapter presents the rules that define photon propagation in the Monte Carlo model as applied to tissues. The treatment is based upon Prah1 *et al.* (1989) except that we deal with a multi-layered tissue instead of a semi-infinite tissue.

#### 3.1 Launching a photon packet

A simple variance reduction technique, implicit photon capture, is used to improve the efficiency of the Monte Carlo simulation. This technique allows one to equivalently propagate many photons as a packet along a particular pathway simultaneously. Each photon packet is initially assigned a weight,  $W$ , equal to unity. The photon is injected orthogonally into the tissue at the origin, which corresponds to a collimated arbitrarily narrow beam of photons.

The current position of the photon is specified by the Cartesian coordinates ( $x$ ,  $y$ ,  $z$ ). The current photon direction is specified by a unit vector,  $\mathbf{r}$ , which can be equivalently described by the directional cosines ( $\mu_x$ ,  $\mu_y$ ,  $\mu_z$ ):

$$\begin{aligned}\mu_x &= \mathbf{r} \cdot \mathbf{x} \\ \mu_y &= \mathbf{r} \cdot \mathbf{y} \\ \mu_z &= \mathbf{r} \cdot \mathbf{z}\end{aligned}\tag{3.1}$$

where  $\mathbf{x}$ ,  $\mathbf{y}$ , and  $\mathbf{z}$  are unit vectors along each axis. The photon position is initialized to (0, 0, 0) and the directional cosines are set to (0, 0, 1). This description of photon position and direction in a Cartesian coordinate system (Witt, 1977) turned out to be simpler than the counterpart in a cylindrical coordinate system (Keijzer *et al.*, 1989).

When the photon is launched, if there is a mismatched boundary at the tissue surface, then some specular reflectance will occur. If the refractive indices of the outside medium and tissue are  $n_1$  and  $n_2$ , respectively, then the specular reflectance,  $R_{sp}$ , is specified (Born *et al.*, 1986; Hecht, 1987):

$$R_{sp} = \frac{(n_1 - n_2)^2}{(n_1 + n_2)^2}\tag{3.2a}$$

If the first layer is glass, which is on top of a layer of medium whose refractive index is  $n_3$ , multiple reflections and transmissions on the two boundaries of the glass layer are considered. The specular reflectance is then computed by:

$$R_{sp} = r_1 + \frac{(1-r_1)^2 r_2}{1-r_1} \quad (3.2b)$$

where  $r_1$  and  $r_2$  are the Fresnel reflectances on the two boundaries of the glass layer:

$$r_1 = \frac{(n_1 - n_2)^2}{(n_1 + n_2)^2} \quad (3.3)$$

$$r_2 = \frac{(n_3 - n_2)^2}{(n_3 + n_2)^2} \quad (3.4)$$

Note that if the specular reflectance is defined as the probability of photons being reflected without interactions with the tissue, then Eqs. 3.2a and 3.2b are not strictly correct although they may be very good estimates of the real specular reflectance for thick tissues. If we want to strictly distinguish the specular reflectance and the diffuse reflectance, we can keep track of the number of interactions experienced by a photon packet. When we score the reflectance, if the number of interactions is not zero, the reflectance is diffuse reflectance. Otherwise, it is specular reflectance. The transmittances can be distinguished similarly.

The photon weight is decremented by  $R_{sp}$ , and the specular reflectance  $R_{sp}$  will be reported to the file of output data.

$$W = 1 - R_{sp} \quad (3.5)$$

### **3.2 Photon's step size**

The step size of the photon packet is calculated based on a sampling of the probability distribution for photon's free path  $s \in [0, \infty)$ , which means  $0 \leq s < \infty$ . According to the definition of interaction coefficient  $\mu_t$ , the probability of interaction per unit pathlength in the interval  $(s', s' + ds')$  is:

$$\mu_t = \frac{-dP\{s \geq s'\}}{P\{s \geq s'\} ds'} \quad (3.6a)$$

or

$$d(\ln(P\{s \geq s'\})) = -\mu_t ds' \quad (3.6b)$$

The above Eq. 3.6b can be integrated over  $s'$  in the range  $(0, s_1)$ , and lead to an exponential distribution, where  $P\{s \geq 0\} = 1$  is used:

$$P\{s \geq s_1\} = \exp(-\mu_t s_1) \quad (3.7)$$

Eq. 3.7 can be rearranged to yield the cumulative distribution function of free path  $s$ :

$$P\{s < s_1\} = 1 - \exp(-\mu_t s_1) \quad (3.8)$$

This cumulative distribution function can be assigned to the uniformly distributed random number  $\xi$  as discussed in Chapter 2. The equation can be rearranged to provide a means of choosing step size:

$$s_1 = \frac{-\ln(1 - \xi)}{\mu_t} \quad (3.9a)$$

or substituting  $\xi$  for  $(1 - \xi)$ :

$$s_1 = \frac{-\ln(\xi)}{\mu_t} \quad (3.9b)$$

Eq. 3.9b gives a mean free path between photon-tissue interaction sites of  $1/\mu_t$  because the statistical average of  $-\ln(\xi)$  is 1, i.e.,  $\langle -\ln(\xi) \rangle = 1$ . There is another approach to obtain Eq. 3.9b. Employing Eq. 3.8, the probability density function of free path  $s$  is:

$$p(s_1) = dP\{s < s_1\}/ds_1 = \mu_t \exp(-\mu_t s_1) \quad (3.10)$$

$p(s_1)$  can be substituted into Eq. 2.5 to yield Eq. 3.9b, where the integration in Eq. 2.5 will be recovered to Eq. 3.8.

In multi-layered turbid media, the photon packet may experience free flights over multiple layers of media before an interaction occurs. In this case, the counterpart of Eq. 3.7 becomes:

$$P\{s \geq s_{\text{sum}}\} = \exp\left(-\sum_i \mu_{ti} s_i\right) \quad (3.11)$$

where  $i$  is an index to a layer, the symbols  $\mu_{ti}$  is the interaction coefficient for the  $i$ th layer, and  $s_i$  is the step size in the  $i$ th layer. The total step size  $s_{\text{sum}}$  is:

$$s_{\text{sum}} = \sum_i s_i \quad (3.12)$$

The summation is over all the layers in which the photon packet has traveled. Eq. 3.11 does not take photon reflection and transmission at boundaries into account because they are processed separately. The sampling equation is obtained by equating Eq. 3.11 to  $\xi$ :

$$\sum_i \mu_{ti} s_i = -\ln(\xi) \quad (3.13)$$

As you may have seen, Eq. 3.9b is just a special case of Eq. 3.13. The sampling can be interpreted as that the total dimensionless step size is  $-\ln(\xi)$ , where dimensionless step size is defined as the product of the dimensional step size  $s_i$  and the interaction coefficient  $\mu_{ti}$ . Since the absorption coefficient and the scattering coefficient of a glass layer are zeros, it does not contribute to the left hand side of Eq. 3.13. The detailed process of Eq. 3.13 will be discussed in Section 3.6 and 3.7. Although Eq. 3.13 looks complicated, it is the theoretical ground for the process in Section 3.6 and 3.7 which looks simpler.

From now on, we will use step size  $s$  instead of  $s_1$  or  $s_{\text{sum}}$  for simplicity. Note that this sampling method involves computation of a logarithm function, which is time-consuming. This is reflected in Section 5.7. Faster methods can be used to avoid the logarithmic computation (Ahrens *et al.*, 1972; Marsaglia, 1961; MacLaren *et al.*, 1964).

### **3.3 Moving the photon packet**

Once the step size  $s$  is specified, the photon is ready to be moved in the tissue. The position of the photon packet is updated by:

$$\begin{aligned} x &\leftarrow x + \mu_x s \\ y &\leftarrow y + \mu_y s \\ z &\leftarrow z + \mu_z s \end{aligned} \quad (3.14)$$

The arrows indicate quantity substitutions. The variables on the left hand side have the new values, and the variables on the right hand side have the old values. In an actual program in C, an equal sign is used for this purpose. The simplicity of Eqs. 3.14 is a major reason for using Cartesian coordinates.

### **3.4 Photon absorption**

Once the photon has taken a step, some attenuation of the photon weight due to absorption by the interaction site must be calculated. A fraction of the photon's current weight,  $W$ , will be deposited in the local grid element. The amount of deposited photon weight,  $\Delta W$ , is calculated:

$$\Delta W = W \frac{\mu_a}{\mu_t} \quad (3.15)$$

The total accumulated photon weight  $A(r, z)$  deposited in that local grid element is updated by adding  $\Delta W$ :

$$A(r, z) \leftarrow A(r, z) + \Delta W \quad (3.16)$$

The photon weight has to be updated as well by:

$$W \leftarrow W - \Delta W \quad (3.17)$$

The photon packet with the new weight  $W$  will suffer scattering at the interaction site (discussed later). Note that the whole photon packet experiences interaction at the end of the step, either absorption or scattering.

### **3.5 Photon scattering**

Once the photon packet has been moved, and its weight decremented, the photon packet is ready to be scattered. There will be a deflection angle,  $\theta \in [0, \pi)$ , and an azimuthal angle,  $\psi \in [0, 2\pi)$  to be sampled statistically. The probability distribution for the cosine of the deflection angle,  $\cos\theta$ , is described by the scattering function<sup>1)</sup> that Henyey and Greenstein (1941) originally proposed for galactic scattering:

$$p(\cos\theta) = \frac{1 - g^2}{2 (1 + g^2 - 2g\cos\theta)^{3/2}} \quad (3.18)$$

where the anisotropy,  $g$ , equals  $\langle \cos\theta \rangle$  and has a value between  $-1$  and  $1$ . A value of  $0$  indicates isotropic scattering and a value near  $1$  indicates very forward directed scattering. Jacques *et al.* (1987) determined experimentally that the Henyey-Greenstein function

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<sup>1)</sup> Note that the scattering function we defined here is a probability density function of  $\cos\theta$ . It has a difference of a constant  $1/2$  with the phase function defined by van de Hulst (1980).

described single scattering in tissue very well. Values of  $g$  range between 0.3 and 0.98 for tissues, but quite often  $g$  is  $\sim 0.9$  in the visible spectrum. Applying Eq. 2.5, the choice for  $\cos\theta$  can be expressed as a function of the random number,  $\xi$ :

$$\cos\theta = \begin{cases} \frac{1}{2g} \left\{ 1 + g^2 - \left[ \frac{1 - g^2}{1 - g + 2g\xi} \right]^2 \right\} & \text{if } g \neq 0 \\ 2\xi - 1 & \text{if } g = 0 \end{cases} \quad (3.19)$$

Next, the azimuthal angle,  $\psi$ , which is uniformly distributed over the interval 0 to  $2\pi$ , is sampled:

$$\psi = 2\pi\xi \quad (3.20)$$

Once the deflection angle and azimuthal angle are chosen, the new direction of the photon packet can be calculated:

$$\begin{aligned} \mu'_x &= \frac{\sin\theta}{\sqrt{1 - \mu_z^2}} (\mu_x \mu_z \cos\psi - \mu_y \sin\psi) + \mu_x \cos\theta \\ \mu'_y &= \frac{\sin\theta}{\sqrt{1 - \mu_z^2}} (\mu_y \mu_z \cos\psi + \mu_x \sin\psi) + \mu_y \cos\theta \\ \mu'_z &= -\sin\theta \cos\psi \sqrt{1 - \mu_z^2} + \mu_z \cos\theta \end{aligned} \quad (3.21)$$

If the angle of the photon packet is too close to normal of the tissue surfaces (e.g.,  $|\mu_z| > 0.99999$ ), then the following formulas should be used:

$$\begin{aligned} \mu'_x &= \sin\theta \cos\psi \\ \mu'_y &= \sin\theta \sin\psi \\ \mu'_z &= \text{SIGN}(\mu_z) \cos\theta \end{aligned} \quad (3.22)$$

where  $\text{SIGN}(\mu_z)$  returns 1 when  $\mu_z$  is positive, and it returns  $-1$  when  $\mu_z$  is negative. Finally, the current photon direction is updated:  $\mu_x = \mu'_x$ ,  $\mu_y = \mu'_y$ ,  $\mu_z = \mu'_z$ .

In the sampling of the two angles  $\theta$  and  $\psi$  and the updating of the directional cosines, trigonometric operations are involved. Because trigonometric operations are computation-intensive, we should try to avoid them whenever possible. The detailed process of the sampling can be found in the function `Spin()` written in the file "mcmlgo.c" (See Appendix A and Appendix B.4).

### **3.6 Reflection or transmission at boundary**

During a step, the photon packet may hit a boundary of the tissue, which is between the tissue and the ambient medium, where the step size  $s$  is computed by Eq. 3.9b. For example, the photon packet may attempt to escape the tissue at the air/tissue interface. If this is the case, then the photon packet may either escape as observed reflectance (or transmittance if a rear boundary is also included) or be internally reflected by the boundary. There are different methods of dealing with this problem when the step size is large enough to hit the boundary. Let us present one of the two approaches used in the program mcml first.

First, a foreshortened step size  $s_1$  is computed:

$$s_1 = \begin{cases} (z - z_0)/(-\mu_z) & \text{if } \mu_z < 0 \\ (z_1 - z)/\mu_z & \text{if } \mu_z > 0 \end{cases} \quad (3.23)$$

where  $z_0$  and  $z_1$  are the  $z$  coordinates of the upper and lower boundaries of the current layer (See Fig. 1.1 for the Cartesian coordinate system). The foreshortened step size  $s_1$  is the distance between the current photon location and the boundary in the direction of the photon propagation. Since the photon direction is parallel with the boundary when  $\mu_z$  is zero, the photon will not hit the boundary. Therefore, Eq. 3.23 does not include the case when  $\mu_z$  is zero. We move the photon packet  $s_1$  to the boundary with a flight free of interactions with the tissue (see Section 3.3 for moving photon packet). The remaining step size to be taken in the next step is updated to  $s \leftarrow s - s_1$ . The photon packet will travel the remaining step size if being internally reflected.

Second, we compute the probability of a photon packet being internally reflected, which depends on the angle of incidence,  $\alpha_i$ , onto the boundary, where  $\alpha_i = 0$  means orthogonal incidence. The value of  $\alpha_i$  is calculated:

$$\alpha_i = \cos^{-1}(|\mu_z|) \quad (3.24)$$

Snell's law indicates the relationship between the angle of incidence,  $\alpha_i$ , the angle of transmission,  $\alpha_t$ , and the refractive indices of the media that the photon is incident from,  $n_i$ , and transmitted to,  $n_t$ :

$$n_i \sin\alpha_i = n_t \sin\alpha_t \quad (3.25)$$

The internal reflectance,  $R(\alpha_i)$ , is calculated by Fresnel's formulas (Born *et al.*, 1986; Hecht, 1987):

$$R(\alpha_i) = \frac{1}{2} \left[ \frac{\sin^2(\alpha_i - \alpha_t)}{\sin^2(\alpha_i + \alpha_t)} + \frac{\tan^2(\alpha_i - \alpha_t)}{\tan^2(\alpha_i + \alpha_t)} \right] \quad (3.26)$$

which is an average of the reflectances for the two orthogonal polarization directions.

Third, we determine whether the photon is internally reflected by generating a random number,  $\xi$ , and comparing the random number with the internal reflectance, i.e.:

$$\text{If } \xi \leq R(\alpha_i), \text{ then photon is internally reflected;} \quad (3.27)$$

$$\text{If } \xi > R(\alpha_i), \text{ then photon escapes the tissue}$$

If the photon is internally reflected, then the photon packet stays on the surface and its directional cosines ( $\mu_x, \mu_y, \mu_z$ ) must be updated by reversing the z component:

$$(\mu_x, \mu_y, \mu_z) \leftarrow (\mu_x, \mu_y, -\mu_z) \quad (3.28)$$

At this point, the remaining step size has to be checked again. If it is large enough to hit the other boundary, we should repeat the above process. If it hits a tissue/tissue interface, we will have to process it according to the following section. Otherwise, if the step size is small enough to fit in this layer of tissue, the photon packet will move with the small step size. At the end of this small step, the absorption and scattering are processed correspondingly.

On the other hand, if the photon packet escapes the tissue, the reflectance or transmittance at the particular grid element ( $r, \alpha_t$ ) must be incremented. The reflectance,  $R_d(r, \alpha_t)$ , or transmittance,  $T_t(r, \alpha_t)$ , is updated by the amount of escaped photon weight,  $W$ :

$$R_d(r, \alpha_t) \leftarrow R_d(r, \alpha_t) + W \quad \text{if } z = 0 \quad (3.29)$$

$$T_t(r, \alpha_t) \leftarrow T_t(r, \alpha_t) + W \quad \text{if } z = \text{the bottom of the tissue.}$$



Since the photon has completely escaped, the tracing of this photon packet ends here. A new photon may be launched into the tissue and traced thereafter. Note that in our simulation, both unscattered transmittance, if any, and diffuse transmittance are scored into  $T_t(r, \alpha_t)$  without distinction although they could be distinguished as we discussed in Section 3.1.

An alternative approach toward modeling internal reflectance deserves mention. Rather than making the internal reflection of the photon packet an all-or-none event, a partial reflection approach can be used each time a photon packet strikes the surface boundary. A fraction  $1 - R(\alpha_i)$  of the current photon weight successfully escapes the tissue, and increments the local reflectance or transmittance array, e.g.,  $R_d(r, \alpha_t) \leftarrow R_d(r, \alpha_t) + W (1 - R(\alpha_i))$ . All the rest of the photon weight will be reflected, and the photon weight is updated as  $W \leftarrow W R(\alpha_i)$ .

Both approaches are available in the program `mcml`, and the users have the option to use either approach depending on the physical quantities that they want to score. A flag in the program can be changed to switch between these two approaches (see Section 5.2). The all-or-none approach is faster, but the partial reflection approach should be able to reduce the variance of the reflectance or transmittance. It is uninvestigated how much variance can be reduced by using the partial reflection approach.

Similar to Section 3.5, the number of trigonometric operations in Eqs. 3.24-3.26 should be minimized for the sake of computation speed. The detailed process of these computations can be found in the function `RFresnel()` written in the file "`mcmlgo.c`" (See Appendix A and Appendix B.4).

### **3.7 Reflection or transmission at interface**

If a photon step size is large enough to hit a tissue/tissue interface, this step may cross several layers of tissue. Consider a photon packet that attempts to make a step of size  $s$  within tissue 1 with  $\mu_{a1}, \mu_{s1}, n_1$ , but hits an interface with tissue 2 with  $\mu_{a2}, \mu_{s2}, n_2$  after a foreshortened step  $s_1$ . Similar to the discussion in the last section, the photon packet is first moved to the interface without interactions, and the remaining photon step size to be taken in the next step is updated to  $s \leftarrow s - s_1$ . Then, we have to determine statistically whether the photon packet should be reflected or transmitted according to the Fresnel's formulas. If the photon packet is reflected, it is processed the same way as in the last section. However, if the photon packet is transmitted to the next layer of tissue, it has to

continue propagation instead of being terminated. Based on Eq. 3.13, the remaining step size has to be converted for the new tissue according to its optical properties:

$$s \leftarrow \frac{s \mu_{t1}}{\mu_{t2}} \quad (3.30)$$

where  $\mu_{t1}$  and  $\mu_{t2}$  are the interaction coefficients for tissue 1 and tissue 2 correspondingly. The current step size  $s$  is again checked for another boundary or interface crossing. The above process is repeated until the step size is small enough to fit in one layer of tissue. At the end of this small step, the absorption and scattering are processed correspondingly.

If the photon packet is in a layer of glass, the photons are moved to the boundary of the glass layer without updating the remaining photon step size because the path length in the glass layer does not contribute to the left hand side of Eq. 3.13. It is important to understand that if a photon packet traverses several layers of tissues, the use of Eq. 3.9b for the step size and the repetitive uses of Eq. 3.30 are based on Eq. 3.13.

### **3.8 Photon termination**

After a photon packet is launched, it can be terminated naturally by reflection or transmission out of the tissue. For a photon packet that is still propagating inside the tissue, if the photon weight,  $W$ , has been sufficiently decremented after many steps of interaction such that it falls below a threshold value (e.g.,  $W_{th} = 0.0001$ ), then further propagation of the photon yields little information unless you are interested in the very late stage of the photon propagation. However, proper termination must be executed to ensure conservation of energy (or number of photons) without skewing the distribution of photon deposition. A technique called roulette is used to terminate the photon packet when  $W \leq W_{th}$ . The roulette technique gives the photon packet one chance in  $m$  (e.g.,  $m = 10$ ) of surviving with a weight of  $mW$ . If the photon packet does not survive the roulette, the photon weight is reduced to zero and the photon is terminated.

$$W \leftarrow \begin{cases} mW & \text{if } \xi \leq 1/m \\ 0 & \text{if } \xi > 1/m \end{cases} \quad (3.31)$$

where  $\xi$  is the uniformly distributed pseudo-random number (see Chapter 2). This method conserves energy yet terminates photons in an unbiased manner. The combination of photon roulette and splitting that is contrary to roulette, may be properly used to reduce variance (Hendricks *et al.*, 1985).

## 4. Scored Physical Quantities

As we mentioned earlier, we record the photon reflectance, transmittance, and absorption during the Monte Carlo simulation. In this chapter, we will discuss the process of these physical quantities in detail. The dimensions of some of the quantities are shown in square brackets at the end of their formulas.

The last cells in  $z$  and  $r$  directions require special attention. Because photons can propagate beyond the grid system, when the photon weight is recorded into the diffuse reflectance or transmittance array, or absorption array, the physical location may not fit into the grid system. In this case, the last cell in the direction of the overflow is used to collect the photon weight. Therefore, the last cell in the  $z$  and  $r$  directions do not give the real value at the corresponding locations. However, the angle  $\alpha$  is always within the bound we choose for it, i.e.,  $0 \leq \alpha \leq \pi/2$ , hence does not cause a problem in the scoring of diffuse reflectance and transmittance.

### 4.1 Reflectance and transmittance

When a photon packet is launched, the specular reflectance is computed immediately. The photon weight after the specular reflection is transmitted into the tissue. During the simulation, some photon packets may exit the media and their weights are accordingly scored into the diffuse reflectance array or the transmittance array depending on where the photon packet exits. After tracing multiple photon packets ( $N$ ), we have two scored arrays  $R_d(r, \alpha)$  and  $T_t(r, \alpha)$  for diffuse reflectance and transmittance respectively. They are internally represented by  $R_{d-r\alpha}[i_r, i_\alpha]$  and  $T_{t-r\alpha}[i_r, i_\alpha]$  respectively in the program. The coordinates of the center of a grid element are computed by:

$$r = (i_r + 0.5) \Delta r \text{ [cm]} \quad (4.1)$$

$$\alpha = (i_\alpha + 0.5) \Delta \alpha \text{ [rad]} \quad (4.2)$$

where  $i_r$  and  $i_\alpha$  are the indices for  $r$  and  $\alpha$ . The raw data give the total photon weight in each grid element in the two-dimensional grid system. To get the total photon weight in the grid elements in each direction of the two-dimensional grid system, we sum the 2D arrays in the other dimension:

$$R_{d-r}[i_r] = \sum_{i_\alpha=0}^{N_\alpha-1} R_{d-r\alpha} [i_r, i_\alpha] \quad (4.3)$$

$$R_{d-\alpha}[i_\alpha] = \sum_{i_r=0}^{N_r-1} R_{d-r\alpha} [i_r, i_\alpha] \quad (4.4)$$

$$T_{t-r}[i_r] = \sum_{i_\alpha=0}^{N_\alpha-1} T_{t-r\alpha} [i_r, i_\alpha] \quad (4.5)$$

$$T_{t-\alpha}[i_\alpha] = \sum_{i_r=0}^{N_r-1} T_{t-r\alpha} [i_r, i_\alpha] \quad (4.6)$$

To get the total diffuse reflectance and transmittance, we sum the 1D arrays again:

$$R_d = \sum_{i_r=0}^{N_r-1} R_{d-r} [i_r] \quad (4.7)$$

$$T_t = \sum_{i_r=0}^{N_r-1} T_{t-r} [i_r] \quad (4.8)$$

All these arrays give the total photon weight per grid element, based on  $N$  initial photon packets with weight unity. To convert  $R_{d-r\alpha}[i_r, i_\alpha]$  and  $T_{t-r\alpha}[i_r, i_\alpha]$  into photon probability per unit area perpendicular to the photon direction per solid angle, they are divided by the projection of the annular area onto a plane perpendicular to the photon exiting direction ( $\Delta a \cos\alpha$ ), the solid angle ( $\Delta\Omega$ ) spanned by a grid line separation in the  $\alpha$  direction around an annular ring, and the total number of photon packets ( $N$ ):

$$R_{d-r\alpha}[i_r, i_\alpha] \leftarrow R_{d-r\alpha}[i_r, i_\alpha] / (\Delta a \cos\alpha \Delta\Omega N) \text{ [cm}^{-2} \text{ sr}^{-1}] \quad (4.9)$$

$$T_{t-r\alpha}[i_r, i_\alpha] \leftarrow T_{t-r\alpha}[i_r, i_\alpha] / (\Delta a \cos\alpha \Delta\Omega N) \text{ [cm}^{-2} \text{ sr}^{-1}] \quad (4.10)$$

where

$$\Delta a = 2 \pi r \Delta r = 2 \pi (i_r + 0.5) (\Delta r)^2 \text{ [cm}^2\text{]} \quad (4.11)$$

$$\Delta \Omega = 4 \pi \sin \alpha \sin(\Delta \alpha / 2) = 4 \pi \sin[(i_\alpha + 0.5) \Delta \alpha] \sin(\Delta \alpha / 2) \text{ [sr]} \quad (4.12)$$

where  $r$  and  $\alpha$  are computed from Eq. 4.1 and Eq. 4.2 respectively. The radially resolved diffuse reflectance  $R_{d-r}[i_r]$  and total transmittance  $T_{t-r}[i_r]$  are divided by the area of the annular ring ( $\Delta a$ ) and the total number of photon packets ( $N$ ) to convert them into photon probability per unit area:

$$R_{d-r}[i_r] \leftarrow R_{d-r}[i_r] / (\Delta a N) \text{ [cm}^{-2}\text{]} \quad (4.13)$$

$$T_{t-r}[i_r] \leftarrow T_{t-r}[i_r] / (\Delta a N) \text{ [cm}^{-2}\text{]} \quad (4.14)$$

The angularly resolved diffuse reflectance  $R_{d-\alpha}[i_\alpha]$  and total transmittance  $T_{t-\alpha}[i_\alpha]$  are divided by the solid angle ( $\Delta \Omega$ ) and the total number of photon packets ( $N$ ) to convert them into photon probability per unit solid angle:

$$R_{d-\alpha}[i_\alpha] \leftarrow R_{d-\alpha}[i_\alpha] / (\Delta \Omega N) \text{ [sr}^{-1}\text{]} \quad (4.15)$$

$$T_{t-\alpha}[i_\alpha] \leftarrow T_{t-\alpha}[i_\alpha] / (\Delta \Omega N) \text{ [sr}^{-1}\text{]} \quad (4.16)$$

The total diffuse reflectance and transmittance are divided by the total number of photon packets ( $N$ ) to get the probabilities:

$$R_d \leftarrow R_d / N \text{ [-]} \quad (4.17)$$

$$T_t \leftarrow T_t / N \text{ [-]} \quad (4.18)$$

where [-] means dimensionless units.

## **4.2 Internal photon distribution**

During the simulation, the absorbed photon weight is scored into the absorption array  $A(r, z)$ .  $A(r, z)$  is internally represented by a 2D array  $A_{rZ}[i_r, i_z]$ , where  $i_r$  and  $i_z$  are the indices for grid elements in  $r$  and  $z$  directions. The coordinates of the center of a grid element can be computed by Eq. 4.1 and the following:

$$z = (i_z + 0.5) \Delta z \quad (4.19)$$

The raw data  $A_{rZ}[i_r, i_z]$  give the total photon weight in each grid element in the two-dimensional grid system. To get the total photon weight in each grid element in the  $z$  direction, we sum the 2D array in the  $r$  direction:

$$A_z[i_z] = \sum_{i_r=0}^{N_r-1} A_{rZ}[i_r, i_z] \quad (4.20)$$

The total photon weight absorbed in each layer  $A_l[\text{layer}]$  and the total photon weight absorbed in the tissue  $A$  can be computed from  $A_z[i_z]$ :

$$A_l[\text{layer}] = \sum_{i_z \text{ in layer}} A_z[i_z] \quad (4.21)$$

$$A = \sum_{i_z=0}^{N_z-1} A_z[i_z] \quad (4.22)$$

where the summation range " $i_z$  in layer" includes all  $i_z$ 's that lead to a  $z$  coordinate in the layer. Then, these quantities are scaled properly to get the densities:

$$A_{rZ}[i_r, i_z] \leftarrow A_{rZ}[i_r, i_z] / (\Delta a \Delta z N) \text{ [cm}^{-3}\text{]} \quad (4.23)$$

$$A_z[i_z] \leftarrow A_z[i_z] / (\Delta z N) \text{ [cm}^{-1}\text{]} \quad (4.24)$$

$$A_l[\text{layer}] \leftarrow A_l[\text{layer}] / N \text{ [-]} \quad (4.25)$$

$$A \leftarrow A / N \text{ [-]} \quad (4.26)$$

The quantity  $A$  gives the photon probability of absorption by the tissue. The 1D array  $A_l[\text{layer}]$  gives the photon probability of absorption in each layer. At this point,  $A_{rZ}[i_r, i_z]$  gives the absorbed photon probability density ( $\text{cm}^{-3}$ ), and can be converted into photon fluence,  $\phi_{rZ}$ , ( $\text{cm}^{-2}$ ) by dividing it by the absorption coefficient  $\mu_a$  ( $\text{cm}^{-1}$ ) of the layer where the current location resides:

$$\phi_{rz}[i_r, i_z] = A_{rz}[i_r, i_z] / \mu_a \text{ [cm}^{-2}\text{]} \quad (4.27)$$

The 1D array  $A_z[i_z]$  gives the photon probability per unit length in the  $z$  direction ( $\text{cm}^{-1}$ ). It can also be divided by the absorption coefficient  $\mu_a$  ( $\text{cm}^{-1}$ ) to yield a dimensionless quantity  $\phi_z[i_z]$ :

$$\phi_z[i_z] = A_z[i_z] / \mu_a \text{ [-]} \quad (4.28)$$

This quantity may seem hard to understand or redundant at first glance. However, the summation of the raw data in Eq. 4.20 is equivalent to the convolution for an infinitely wide flat beam in Eq. 7.15 to be discussed in Chapter 7. The equivalence can be shown as follows. According to Eqs. 4.20, 4.23 and 4.24, the final converted  $A_z[i_z]$  and  $A_{rz}[i_r, i_z]$  have the following relation:

$$A_z[i_z] = \sum_{i_r=0}^{N_r-1} A_{rz}[i_r, i_z] \Delta a(i_r) \quad (4.29)$$

where  $\Delta a(i_r)$  is computed in Eq. 4.11, but we stress that it is a function of  $i_r$  in Eq. 4.29. Employing Eqs. 4.27 and 4.28, Eq. 4.29 can be converted to:

$$\phi_z[i_z] = \sum_{i_r=0}^{N_r-1} \phi_{rz}[i_r, i_z] \Delta a(i_r) \quad (4.30)$$

This is a numerical solution of the following integral:

$$\phi_z(z) = \int_0^{\infty} \phi_{rz}(r, z) 2 \pi r \, dr \quad (4.31)$$

Eq. 4.31 is essentially Eq. 7.15 for an infinitely wide flat beam with a difference of constant  $S$ , where  $S$  is the power density of the infinitely wide flat beam. The equivalence between Eq. 4.31 and Eq. 7.15 can be seen after substituting  $\phi_z(z)$  for  $F(r, z)$ ,  $\phi_{rz}(r, z)$  for  $G(r'', z)$ , and  $r$  for  $r''$ . Therefore,  $\phi_z[i_z]$  gives the fluence for an infinitely wide flat beam with a difference of a constant which is the power density  $S$ .

The program `mcml` will only report  $A_{rz}[i_r, i_z]$  and  $A_z[i_z]$  instead of  $\phi_{rz}[i_r, i_z]$  and  $\phi_z[i_z]$ . The program `conv` will be set up to convert  $A_{rz}[i_r, i_z]$  and  $A_z[i_z]$  into  $\phi_{rz}[i_r, i_z]$  and  $\phi_z[i_z]$ .

### 4.3 Issues regarding grid system

In our Monte Carlo simulation, we always set up a grid system. The computation results will be limited by the finite grid size. This section will discuss what is the best that one can do.

#### Position of average value for each grid element

The simulation provides the average value of the scored physical quantities in each grid element. Now, the question is at what position should that averaged value be assigned? One can argue that there is no best point because the exact answer to the physical quantities is unknown. However, under linear approximations of the physical quantities in each grid element, we can find the best point for each grid point. The linear approximations can be justified for small grid size in most cases because the higher order terms are considerably less than the linear term. Some special occasions will be discussed subsequently.

Let us discuss the grid system in the  $r$  direction first because  $r$  is the variable over which the convolution for photon beams of finite size will be implemented (see Chapter 7). The grid system in the  $r$  direction uses  $\Delta r$  as the grid separation with a total of  $N$  grid elements. The index to each grid element is denoted by  $n$ . The center of each grid element is denoted by  $r_n$ :

$$r_n = (n + 0.5) \Delta r \quad (4.32)$$

As we have mentioned, the Monte Carlo simulation actually approximates the average of the physical quantity  $Y(r)$  in each grid element, where  $Y(r)$  can be the diffuse reflectance, diffuse transmittance, and internal fluence  $A_{rz}(r, z)$  for a particular  $z$  value.

$$\langle Y(r) \rangle = \frac{1}{2 \pi r_n \Delta r} \int_{r_n - \Delta r/2}^{r_n + \Delta r/2} Y(r) 2 \pi r dr \quad (4.33)$$

where  $2 \pi r_n \Delta r$  is the area of the ring or the circle when  $n = 0$ .

If  $Y(r)$  in each grid element is approximated linearly, we can prove that there exists a best point  $r_b$  to satisfy:



$$\langle Y(r) \rangle = Y(r_b) \quad (4.34)$$

where

$$r_b = r_n + \frac{\Delta r}{12} \quad (4.35)$$

Proof:  $Y(r)$  is approximated by a Taylor series about  $r_b$  expanded to the first order:

$$Y(r) = Y(r_b) + (r - r_b) Y'(r_b) \quad (4.36)$$

Substituting Eq. 4.36 into Eq. 4.33 yields:

$$\begin{aligned} \langle Y(r) \rangle &= \frac{1}{2 \pi r_n \Delta r} \int_{r_n - \Delta r/2}^{r_n + \Delta r/2} [Y(r_b) + (r - r_b) Y'(r_b)] 2 \pi r \, dr \\ &= \frac{Y(r_b)}{2 \pi r_n \Delta r} \int_{r_n - \Delta r/2}^{r_n + \Delta r/2} 2 \pi r \, dr + \\ &\quad \frac{Y'(r_b)}{2 \pi r_n \Delta r} \int_{r_n - \Delta r/2}^{r_n + \Delta r/2} (r - r_b) 2 \pi r \, dr \\ &= \frac{Y(r_b)}{2 \pi r_n \Delta r} [\pi r^2] \Big|_{r_n - \Delta r/2}^{r_n + \Delta r/2} + \frac{Y'(r_b)}{2 \pi r_n \Delta r} (\pi/3) [2 r^3 - 3 r_b r^2] \\ &\quad \Big|_{r_n - \Delta r/2}^{r_n + \Delta r/2} \\ &= \frac{Y(r_b)}{2 \pi r_n \Delta r} [2 \pi r_n \Delta r] + \frac{Y'(r_b)}{2 \pi r_n \Delta r} (\pi/3) [2 \Delta r (3 r_n^2 + \frac{(\Delta r)^2}{4}) - 3 r_b r_n] \\ &= Y(r_b) + Y'(r_b) [r_n + \frac{(\Delta r)^2}{12} - r_b] \end{aligned}$$

or

$$\langle Y(r) \rangle = Y(r_b) + Y'(r_b) \left[ r_n + \frac{(\Delta r)^2}{12 r_n} - r_b \right] \quad (4.37)$$

If we set the term in the square bracket in Eq. 4.37 to zero, and solve for  $r_b$ , we obtain:

$$r_b = r_n + \frac{(\Delta r)^2}{12 r_n} \quad (4.38a)$$

and Eq. 4.37 becomes:

$$\langle Y(r) \rangle = Y(r_b) \quad (4.39)$$

Eq. 4.38a can be reformulated:

$$r_b = r_n + \frac{\Delta r}{12 r_n} \Delta r \quad (4.38b)$$

Q.E.D.

We can substitute Eq. 4.32 into the second term of Eq. 4.38b:

$$r_b = \left[ (n + 0.5) + \frac{1}{12 (n + 0.5)} \right] \Delta r \quad (4.38c)$$

$$\text{When } n = 0, r_b = \left[ 0.5 + \frac{1}{6} \right] \Delta r = \frac{2}{3} \Delta r$$

$$\text{When } n = 1, r_b = \left[ 1.5 + \frac{1}{18} \right] \Delta r \approx 1.556 \Delta r$$

$$\text{When } n = 2, r_b = \left[ 2.5 + \frac{1}{30} \right] \Delta r \approx 2.533 \Delta r$$

$$\text{When } n = 3, r_b = \left[ 3.5 + \frac{1}{42} \right] \Delta r \approx 3.524 \Delta r$$

$$\text{When } n = 4, r_b = \left[ 4.5 + \frac{1}{54} \right] \Delta r \approx 4.519 \Delta r$$

...

It is observed that the best point deviates from the center of each grid element, and the smaller the index to the grid box, the larger the deviation. As the index  $n$  becomes large, the best point approaches the center of the grid element. This behavior is due to the

$2 \pi r$  factor in Eq. 4.33. A similar factor does not exist for the  $z$  direction, and the best points for the  $z$  direction should be the centers of each grid element.

The computation results of a Monte Carlo simulation with a selected grid system always have finite precision which is fundamentally limited by the finite grid size. The above theorem only gives the points where the function values are best represented by the simulated results.

#### Effects of the first photon-tissue interaction

The above theorem assumed differentiability of  $Y(r)$ , where  $Y(r)$  can represent the diffuse reflectance  $R_d(r)$ , the diffuse transmittance  $T_d(r)$ , and the internal fluence  $\phi_{rz}(r, z)$  at a particular  $z$  value. This assumption should hold for the diffuse reflectance and the diffuse transmittance. However, for the internal fluence, the on- $z$ -axis fluence is a delta function for an impulse response (responses to an infinitely narrow photon beam). Therefore, you cannot assume the differentiability of the function  $\phi_{rz}(r, z)$  at  $r$  equal zero, i.e.,  $\phi_{rz}(r=0, z)$ . The best solution to this problem has been provided by Gardner *et al.* (1992b). They keep track of the first photon interactions with the medium, which are always on the  $z$ -axis, separately from the rest of the interactions. Therefore, the function  $\phi_{rz}(r, z)$  will not include the first photon-tissue interaction which yield a delta function. This approach ensures a differentiable  $\phi_{rz}(r, z)$  at  $r$  equal zero besides its better accuracy.

In the current version (version 1.0) of *mcml*, Gardner *et al.*'s approach is not yet implemented although we intend to add this in the later version. However, the result from *mcml* will still be correct within the spatial resolution of the grid size in the  $r$  direction. Although nobody will use Monte Carlo to simulate the responses in an absorption-only semi-infinite medium, let us use this simple example to illustrate what we mean. In this case, Gardner *et al.*'s approach will yield an exponentially decaying response on the  $z$  axis which is a delta function of  $r$ . The version 1.0 of *mcml* will yield the same exponentially decaying response in the first grid elements which is not a delta function because of the finite volume of the grid elements. However, as the grid separation  $\Delta r$  is made sufficiently small, the result approaches Gardner *et al.*'s.

So far the discussion has nothing to do with convolution for photon beams of finite size which will be discussed in Chapter 7. According to Gardner *et al.* (1992b), the error in the convolution caused by not scoring the first interactions separately will be small for Gaussian beams whose radius is at least three times larger than the grid separation  $\Delta r$ . As

---

we will discuss in Section 7.4, our extended trapezoidal integration, instead of integrating over the original grid points, in the convolution program `conv` should further decrease the error. Of course, when the on-z-axis interactions are considered separately, our convolution program `conv` is not subject to this limitation on the radius of the Gaussian beam. In contrast, if the integration is approximated by computing the integrand over the original grid points, the radius of the photon beam should still be large enough to yield reasonable integration accuracy.

Since this theorem is a late development, it has not been implemented in the programs (`mcml` and `conv`) yet. We plan to implement it in the next release (see Appendix H).

## **5. Programming mcml**

The simulation is written in ANSI Standard C (Plauger *et al.*, 1989, Kelley *et al.*, 1990), which makes it possible to execute the program on any computers that support ANSI Standard C. So far, the program has been successfully tested on Macintosh, IBM PC compatibles, Sun SPARCstation 2, IBM RISC/6000 POWERstation 320, and Silicon Graphics IRIS workstation. This chapter mainly describes several rules, the important constants and the data structures used in the program, the algorithm to trace photon packets, flow of the program, and the timing profile of the program. Prior knowledge of C is assumed to fully understand this chapter. The flow of the program is listed in detail in Appendix A. The complete source code is listed in Appendix B file by file. In Appendix C, we have provided a make file used by make utilities on UNIX machines. Appendix D and E are a template of input data file and a sample output data file respectively. Appendix F gives several C Shell scripts for UNIX users. The information needed to obtain the program is detailed in Appendix G.

### **5.1 Programming rules and conventions**

When we write this program, we have followed the following rules and conventions:

1. Conform to ANSI Standard C so that the program can be executed on a variety of computers.
2. Avoid global variables whenever possible. This program has not defined any global variables so far.
3. Avoid hard limits on the program. For example, we removed the limits on the number of array elements by dynamic allocation at run time. This means that the program can accept any number of layers or gridlines as long as the memory permits.
4. Preprocessor names are all capital letters, e.g.,  

```
#define PREPROCESSORS
```
5. For global variables, function names, or data types, first letter of each word is capital, and words are connected without underscores, e.g.,

```
short GlobalVar;
```

6. For dummy variables, first letter of each word is capital, and words are connected by underscores, e.g.,

```
void NiceFunction(char Dummy_Var);
```

7. Local variables are all lower cases, and words are connected by underscores, e.g.,

```
short local_var;
```

## **5.2 Several constants**

There are several important constants defined in the header file `mcml.h` or the source files `mcmlmain.c` and `mcmlgo.c`. They are listed in Table 5.1, and may be altered according to your special need.

The constant `STRLEN` is used in the program to define string length. `WEIGHT` is the threshold photon weight, below which the photon packet will go through a roulette. This photon packet with small weight  $W$  has a chance of `CHANCE` to survive with a new weight of  $W/\text{CHANCE}$ . `COSZERO` and `COS90D` are used for the computation of reflection with Fresnel's formulas, and for the computation of new photon directional cosines. When  $|\cos\alpha| > \text{COSZERO}$ ,  $\alpha$  is considered very close to 0 or 180°. When  $|\cos\alpha| < \text{COS90D}$ ,  $\alpha$  is considered very close to 90°.

When `THINKCProfiler` is 1, the profiler of THINK C compiler (Symantec, 1991) on Macintosh can be used to monitor the timing profile of the program regarding each function (see Section 5.7). When `GNUCC` is 1, the code can be compiled with GNU C compiler (`gcc`) from the Free Software Foundation, which does not support several functions such as `difftime()` although being claimed to conform to ANSI C standards. Therefore, the timing modules in the program will not work when `GNUCC` is 1, although the program will otherwise operate normally. When `STANDARDTEST` is 1, the random number generator will generate a fixed sequence of random numbers after being fed a fixed seed. This feature is used to debug the program. `STANDARDTEST` should be set to 0 normally, which makes the random number generator use the current time as the seed. When `PARTIALREFLECTION` is set to 0, the all-or-none simulation mechanism of photon internal reflection at a boundary (e.g., air/tissue boundary) described in Section 3.6 is used, where the photon packet is either totally reflected or totally transmitted determined by the comparison of the Fresnel reflectance and a random number. Otherwise when

PARTIALREFLECTION is set to 1, the photon packet will be partially reflected and transmitted. Normally we set PARTIALREFLECTION to 0 because the all-or-none simulation is faster.

**Table 5.1.** Important constants in the program mcml.

Constants	File	Value	Meaning
WEIGHT	mcml.h	$1 \times 10^{-4}$	threshold weight
CHANCE	mcml.h	0.1	chance of surviving a roulette
STRLEN	mcml.h	256	string length
COSZERO	mcmlgo.c	$1 - 1 \times 10^{-12}$	cosine of $\sim 0$
COS90D	mcmlgo.c	$1 \times 10^{-6}$	cosine of $\sim 90^\circ$
THINKCPROFILER	mcmlmain.c	1/0	switch for THINK C profiler on Macintosh
GNUCC	mcmlmain.c	1/0	switch for GNU C compiler
STANDARDTEST	mcmlgo.c	1/0	switch for fixed sequence of random numbers
PARTIAL- REFLECTION	mcmlgo.c	1/0	switch for partial internal reflection at boundary

### 5.3 Data structures and dynamic allocations

Data structures are an important part of the program. Related parameters are logically organized by structures such that the program is easier to write, read, maintain, and modify. The parameters for a photon packet are grouped into a single structure defined by:

```
typedef struct {
    double x, y, z; /* Cartesian coordinates.[cm] */
    double ux, uy, uz; /* directional cosines of a photon. */
    double w; /* weight. */
    Boolean dead; /* 1 if photon is terminated. */
    short layer; /* index to layer where the photon packet resides.*/
    double s; /* current step size. [cm]. */
    double sleft; /* step size left. dimensionless [-]. */
} PhotonStruct;
```

The location and the traveling direction of a photon packet are described by the Cartesian coordinates  $x$ ,  $y$ ,  $z$ , and the directional cosines ( $u_x$ ,  $u_y$ ,  $u_z$ ) respectively. The current weight of the photon packet is denoted by the structure member  $w$ . The member `dead`, initialized to be 0 when the photon packet is launched, represents the status of a photon

packet. If the photon packet has exited the tissue or it has not survived a roulette when its weight is below the threshold weight, then the member `dead` is set to 1. It is used to signal the program to stop tracing the current photon packet. Note that the type `Boolean` is not an internal data type in ANSI Standard C. It is defined to be type `char` in our header file `mcml.h`. The member `layer` is the index to the layer where the photon packet resides. Type `short`, whose value ranges between  $-32768$  ( $2^{15}$ ) and  $+32768$  (Plauger *et al.*, 1989), is used for the member `layer`. It is defined for computation efficiency although the layer can always be identified according to the Cartesian coordinates of the photon packet and the geometric structure of the media. The member `layer` is updated only when the photon packet crosses tissue/tissue interfaces. The member `s` is the step size in cm for the current step. The member `sleft` is used to store the unfinished step size in dimensionless units when a step size is large enough to hit a boundary or interface. For example, if a selected step size  $s$  is long enough to hit a boundary of the current layer with interaction coefficient  $\mu_t$  as explained in Section 3.6, a foreshortened step size  $s_1$  is chosen as the current step size, and the unfinished step size has to be stored. In the program, the following assignments are implemented: the member `s` =  $s_1$  and the member `sleft` =  $(s - s_1) \mu_t$ . Note that we store the unfinished step size in dimensionless unit, therefore, we only need to know the interaction coefficient of the current layer to convert the step size back in cm when the photon packet crosses layers.

The parameters that are needed to describe a layer of tissue are grouped into one structure:

```
typedef struct {
    double z0, z1;      /* z coordinates of a layer. [cm] */
    double n;          /* refractive index of a layer. */
    double mua;       /* absorption coefficient. [1/cm] */
    double mus;       /* scattering coefficient. [1/cm] */
    double g;         /* anisotropy. */

    double cos_crit0, cos_crit1;
} LayerStruct;
```

The Cartesian coordinates of the top and bottom boundaries are denoted by `z0` and `z1` respectively. The refractive index, absorption coefficient, scattering coefficient, and anisotropy factor of a layer of medium are represented by the members `n`, `mua`, `mus`, and `g` respectively. The cosines of the critical angles are denoted by the members `cos_crit0` and `cos_crit1` respectively. They are computed with the relative refractive index of this layer with respect to the two neighbor layers.





```

double * Rd_r; /* 1D radial distribution of diffuse */
              /* reflectance. [1/cm2] */
double * Rd_a; /* 1D angular distribution of diffuse */
              /* reflectance. [1/sr] */
double Rd; /* total diffuse reflectance. [-] */

double ** A_rz; /* 2D probability density in turbid */
               /* media over r & z. [1/cm3] */
double * A_z; /* 1D probability density over z. */
              /* [1/cm] */
double * A_l; /* each layer's absorption */
              /* probability. [-] */
double A; /* total absorption probability. [-] */

double ** Tt_ra; /* 2D distribution of total */
                /* transmittance. [1/(cm2 sr)] */
double * Tt_r; /* 1D radial distribution of */
               /* transmittance. [1/cm2] */
double * Tt_a; /* 1D angular distribution of */
               /* transmittance. [1/sr] */
double Tt; /* total transmittance. [-] */
} OutStruct;

```

The member  $R_{sp}$  is the specular reflectance. The pointer  $Rd_{ra}$  will be allocated dynamically, and used equivalently as if it is a 2D array over  $r$  and  $\alpha$ .  $Rd_{ra}$  is the internal representation of diffuse reflectance  $R_d(r, \alpha)$  discussed in Section 4.1. The members  $Rd_r$  and  $Rd_a$  are the 1D diffuse reflectance distributions over  $r$  and  $\alpha$  respectively. The member  $Rd$  is the total diffuse reflectance  $R_d$ . The member  $A_{rz}$  is the representation of the 2D internal photon distribution  $A(r, z)$  (see Section 4.2). The members  $A_z$  and  $A_l$  are the corresponding 1D internal photon distributions with respect to  $z$  and layers respectively. The member  $A$  is the probability of photon absorption by the whole tissue. The members for transmittance are analogous to these for reflectance except that there is no distinction between unscattered transmittance and diffuse transmittance. All the transmitted photon weight is scored into the arrays.

In the above defined structures, pointers are used to denote the 2D or 1D arrays. These pointers are dynamically allocated at run time according to user's specifications. Therefore, the user can use different numbers of layers or numbers of grid elements without changing the source code of the program. This provides the flexibility of the program and the efficiency of memory utilization. The dynamic allocation procedures are modified from Press (1988). Only 1D array allocation will be presented here, and the matrix allocation can be found in Appendix B.5 -- "mcmlnr.c".

```

double *AllocVector(short nl, short nh)
{
    double *v;
    short i;

```

```
v=(double *)malloc((unsigned) (nh-nl+1)*sizeof(double));
if (!v) nrerror("allocation failure in vector()");

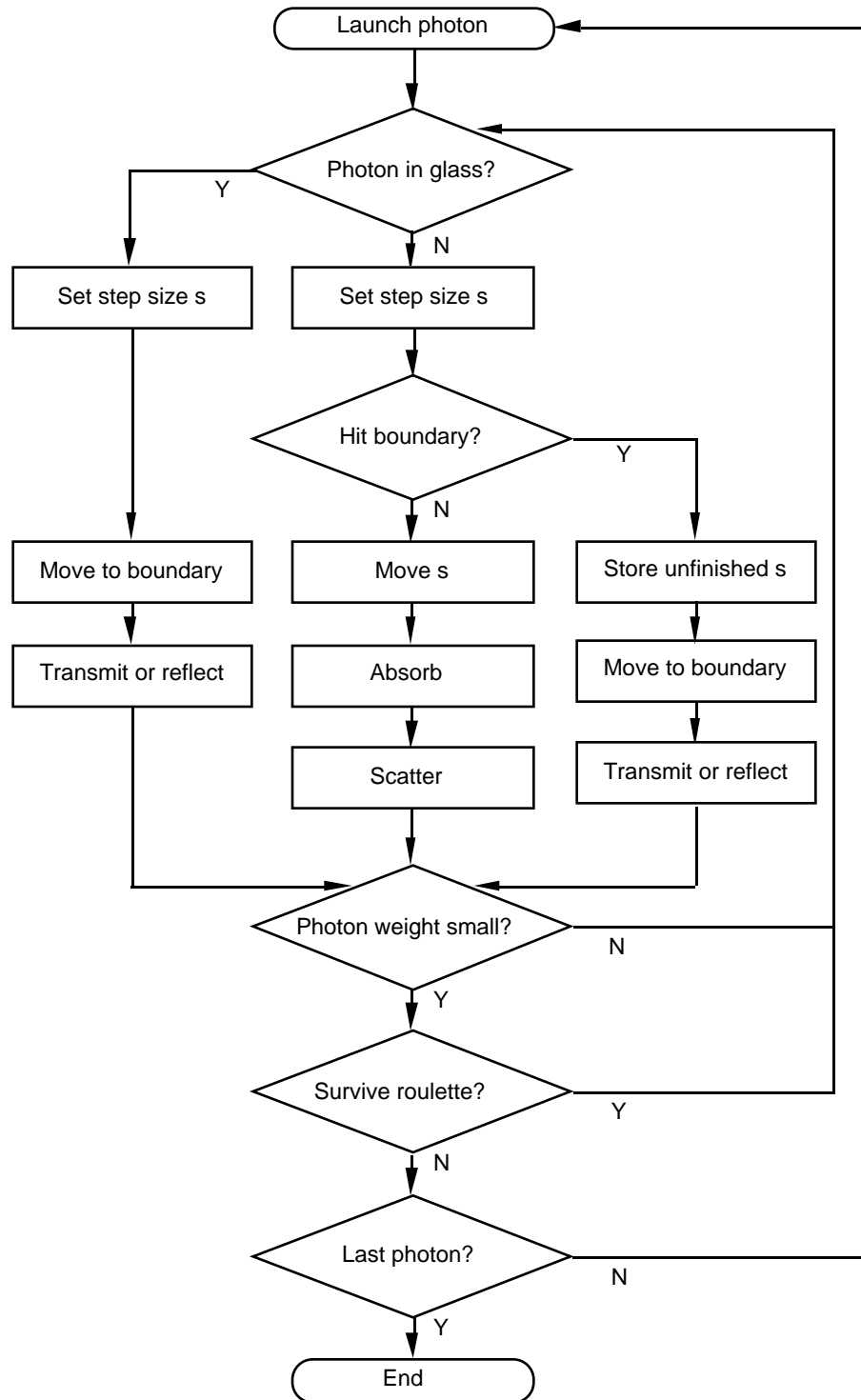
v -= nl;
for(i=nl;i<=nh;i++) v[i] = 0.0; /* init. */
return v;
}
```

This function returns a pointer, which points to an array of elements. Each element is a double precision floating point number. The index range of the array is from `nl` to `nh` inclusive. In our simulation, `nl` is always 0, which is the default value in C. This function also initializes all the elements equal to zero.

#### **5.4 Flowchart of photon tracing**

Fig. 5.1 indicates the basic flowchart for the photon tracing part of the Monte Carlo calculation as described in Chapter 3. Many boxes in the flowchart are direct implementations of the discussions in Chapter 3. This chart also includes the situation where the photon packet is in a glass, in which absorption and scattering do not exist. In this case, the photon packet will be moved to the boundary of the glass layer in the current photon direction. Then, we have to determine statistically whether the photon packet will cross the boundary or be reflected according to the Fresnel's formulas.

The box "Launch photon" initializes the photon packet position, direction, weight, and several other structure members including `ds` and `dsleft` in `PhotonStruct`. The flow control box "Photon in glass?" determines whether the current layer is a glass layer or tissue layer.



**Fig. 5.1.** Flowchart for Monte Carlo simulation of multi-layered tissue.

When the photon packet is in glass layers, which have no absorption or scattering, the box "Set step size  $s$ " chooses the distance between the current photon position and the boundary in the direction of the photon movement as the step size. The box "Move to

boundary" updates the position of the photon packet. Now, as the photon packet is on the boundary, two approaches of processing photon transmission and reflection are supported in the box "Transmit or reflect" as discussed in Section 3.6. If the constant `PARTIALREFLECTION` is zero, the box determines whether the photon packet should cross the boundary or be reflected according to the Fresnel reflectance in an all-or-none fashion. If the photon packet is reflected, the propagation direction should be updated. Otherwise, if the photon packet crosses the interface into another layer of tissue, the propagation direction and the index to the layer are updated. If the photon packet crosses the boundary and moves out of the medium, the photon packet is terminated and the photon weight is scored into the array for reflectance or transmittance depending on where the photon packet exits. If the constant `PARTIALREFLECTION` is one, the box "Transmit or reflect" deals with ambient medium/tissue interface differently. Part of the photon weight is transmitted to the ambient medium as reflectance or transmittance, and the rest of the weight will be reflected and continue propagation. Normally we set `PARTIALREFLECTION` to 0 because the all-or-none simulation is faster (see Section 3.6).

In tissue layers, the box "Set step size *s*" sets the step size to the unfinished step size according to the structure member `sleft` if `sleft` is not zero. Otherwise, it sets the step size according to the interaction coefficient of the medium. With the chosen step size *s*, the box "Hit boundary?" identifies whether the step size is long enough to hit the boundary of the current layer.

If the step does not hit the boundary, then the box "Move *s*" will update the position of the photon packet. Then, the box "Absorb" will deposit a portion of the photon packet weight in the local grid element, and the box "Scatter" will determine the new traveling direction for the rest of the photon packet after absorption.

If the step hits the boundary, then the step size *s* is foreshortened. The foreshortened step size is the distance between the photon position and the boundary in the direction of the photon movement, and the unfinished step size is stored by the box "Store unfinished *s*". The stored unfinished step size in dimensionless units will be used by the box "Set step size *s*" for tissue layers to generate the next step size. The next two boxes "Move to boundary" and "Transmit or reflect" function the same as for the glass layer.

At this point, the photon weight and the structure member `dead` are checked in the box "Photon weight small?". If the photon packet is dead, it will jump to the box "Last photon?" (transition not shown in the flowchart). If the photon packet is still alive and its

weight exceeds  $w_{th}$ , it will start the next step of propagation. If the photon packet is still alive and its weight is lower than  $w_{th}$ , it has to experience a roulette in the box "Survive roulette?". If the photon packet survives the roulette, it will start the next step of propagation. Otherwise, the photon packet is terminated and the box "Last photon?" determines whether to end the simulation or to start tracing a new photon packet.

### **5.5 Flow of the program mcml**

A flow graph of the mcml source code has been generated using the UNIX command `cflow` under SunOS. Each line of output begins with a reference number, i.e., a line number, followed by a suitable number of tabs indicating the level, then the name of the global (normally only a function not defined as an external or beginning with an underscore), a colon, and its definition. The definition consists of an abstract type declaration (for example, `char *`), and delimited by angle brackets, the name of the source file and the line number where the definition was found.

Once a definition of a name has been printed, subsequent references to that name contain only the reference number of the line where the definition may be found. For undefined references, only `<>` is printed.

The list in Fig. 5.2 is generated by command: `cflow -d2 mcml*.c`. The option "-d2" limits the nesting depth to 2. The command output with all the nesting levels is shown in Appendix A.

```

1  main: char(), <mcmlmain.c 198>
2    ShowVersion: void*(), <mcmllio.c 49>
3      CenterStr: char*(), <mcmllio.c 28>
4      puts: <>
5    GetFnameFromArgv: void*(), <mcmlmain.c 150>
6      strcpy: <>
7    GetFile: struct*(), <mcmllio.c 94>
8      printf: <>
9      scanf: <>
10     strlen: <>
11     exit: <>
12     fopen: <>
13    CheckParm: void*(), <mcmllio.c 514>
14      ReadNumRuns: short(), <mcmllio.c 205>
15      printf: 8
16      ReadParm: void*(), <mcmllio.c 425>
17      FnameTaken: char(), <mcmllio.c 487>
18      sprintf: <>
19      free: <>
20      nrerror: void*(), <mcmlnr.c 19>
21      FreeFnameList: void*(), <mcmllio.c 500>
22      rewind: <>
23    ReadNumRuns: 14
24    ReadParm: 16
25    DoOneRun: void*(), <mcmlmain.c 163>
26      InitOutputData: void*(), <mcmllio.c 546>
27      Rspherical: double(), <mcmlgo.c 117>
28      PunchTime: long(), <mcmlmain.c 60>
29      ReportStatus: void*(), <mcmlmain.c 122>
30      LaunchPhoton: void*(), <mcmlgo.c 143>
31      HopDropSpin: void*(), <mcmlgo.c 726>
32      ReportResult: void*(), <mcmlmain.c 133>
33      FreeData: void*(), <mcmllio.c 581>
34    fclose: <>

```

**Fig. 5.2.** Flow of mcml.

The names of most functions well describe what they do. The function `ShowVersion()` prints the name of the program, the names and address of the authors of the program, and the version of the program. The function `GetFnameFromArgv()` get an input data filename from the command line input for UNIX users or DOS users. Macintosh OS does not allow command line input. The function `GetFile()` is used to get the pointer to the file stream for the input data file. The function `CheckParm()` checks the input parameters. If the `CheckParm()` detects an error, it will exit the program. Otherwise, if all the input parameters pass the error check by the function `CheckParm()`, independent simulation runs will be implemented one by one. For each independent run, the function `ReadParm()` obtains the input parameters, and the function `DoOneRun()` does the simulation and reports the results to the output data file.

After all the input parameters are checked by `CheckParm()`, the file pointer is rewound to the beginning of the file stream so that the input parameters can be read again by the functions `ReadNumRuns()` and `ReadParm()`. The function `ReadNumRuns()` gets how many independent simulations are to be specified in this input data file. The function `ReadParm()` only reads the input parameters for one independent run.

Under the function `DoOneRun()`, the function `PunchTime()` provides the user time and the real time used so far by the current simulation run. The function `ReportStatus()` fetches the real time and predicts when the current simulation run will finish. However, these timing functions will not work if the source code is compiled by a GNU C compiler. The function `LaunchPhoton()` initializes a photon packet. The function `HopDropSpin()` moves the photon packet, deposits some photon packet weight, scatters the packet, and deals with the boundary. After the given number of photon packets are traced, the results are properly processed (see Chapter 4) and then written to an output file by the function `ReportResult()`.

## **5.6 Multiple simulations**

The program can do any number of independent simulations sequentially without being subject to memory limit. It checks the parameters of one simulation after another before starting the simulation. If it detects an error in the input data file, the program stops the execution. Otherwise, it reads in the parameters of one independent simulation at a time and starts the simulation. At the end of the simulation, it writes the results to the output data file whose name is specified by the input data file. The next independent run will be processed thereafter. The users should try to make sure not to use the same output filenames for different simulations, although the program checks against duplicated output filenames.

To check against duplicated filenames specified in an input data file, we set up a linear linked list to store the filenames specified in the input data file. Each new filename is compared with every node of the filename list. If the name is already taken, the program notifies the user of the name, and exits to the system. Otherwise, if no filename is duplicated, the program deletes the filename list to release the memory, and continues execution.



### 5.7 Timing profile of the program

The timing profile of the program mcml indicates how to improve the efficiency of the program by logging how much time the program spends on each function. Profilers are available in a few compilers including C compilers of UNIX operating systems, and THINK C compiler on Macintosh. We used the THINK C 5.0.1 profiler here (Symantec, 1991). To log the timings, we turn on the flag THINKCProfiler to 1 in mcmlmain.c, and check the "Generate profiler calls" check box in the Debugging page of the "Options..." dialog box in the THINK C compiler.

The following input file is used (see Section 9.1 for how to name the input file) to test the profile, where only 100 photon packets are traced. The optical parameters of the tissue are: refractive index  $n = 1.37$ , absorption coefficient  $\mu_a = 1 \text{ cm}^{-1}$ , scattering coefficient  $\mu_s = 100 \text{ cm}^{-1}$ , anisotropy factor  $g = 0.9$ , and thickness  $d = 0.1 \text{ cm}$ .

```

1.0                # file version
1                  # number of runs

prof.mco          A                # output filename, ASCII/Binary
100                # No. of photons
1E-2  1E-2        # dz, dr
100  100  1        # No. of dz, dr & da.

1                  # No. of layers
# n  mua  mus  g    d                # One line for each layer
1.0                # n for medium above.
1.37  1    100  0.90  0.1            # layer 1
1.0                # n for medium below.

```

The profiler output is listed in Table 5.2. The heading "Function" gives the name of a function. The headings "Minimum", "Maximum" and "Average" give the minimum, maximum and average time spent in a routine respectively. The unit of time here is a unit of the VIA 1 timer. Each unit is 1.2766  $\mu\text{sec}$  (approximately 780,000 in a second). The heading "%" is the percentage of profiling period spent in the routine, where the profiling period is the accumulated time spent in routines that were compiled with the "Generate profiler calls" options on. The heading "Entries" is the number of times the routine was called.

**Table 5.2.** Timing profile of the program mcml.

Function	Minimum	Maximum	Average	%	Entries
AllocMatrix	2507	134153	46662	0	3
AllocVector	65	319	169	0	6
CrossDnOrNot	53	670	145	0	95
CrossOrNot	40	631	66	0	175
CrossUpOrNot	53	635	144	0	80
Drop	166	887	245	5	3554
HitBoundary	38	622	62	1	3729
Hop	40	595	59	1	3729
HopDropSpin	52	711	74	1	3729
HopDropSpinInTissue	111	815	242	5	3729
InitOutputData	314	314	314	0	1
LaunchPhoton	35	123	59	0	100
PredictDoneTime	56472	61201	58638	3	9
PunchTime	76	116	104	0	10
RFresnel	300	905	411	0	105
RandomNum	37	735	67	4	10937
RecordR	1099	2293	1690	0	46
RecordT	1363	2396	1761	0	54
ReportStatus	19	790	90	0	100
Rspecular	58	58	58	0	1
Spin	914	2157	1412	<b>33</b>	3554
SpinTheta	72	665	102	2	3554
StepSizeInTissue	36	2094	1378	<b>33</b>	3729
ran3	27	1187	44	3	10938

From the percentage column, we observe that the functions `Spin()` and `StepSizeInTissue()` take most of the computation time. They are the primary places to modify if we need to improve the efficiency. The function `StepSizeInTissue()` takes a long time because of the logarithmic operation. The function `PredictDoneTime()` apparently takes much computation time too. This is because we simulated only 100 photon packets. This function will be called for a fixed number of times (10 times) for a

simulation no matter how many photon packets are simulated. Therefore, its percentage will decrease linearly with the number of photon packets to be simulated. Note that we made the profiler include only the main part of the simulation (See file mcmlmain.c in Appendix B). Therefore, the functions for input or output of data are not included since they do not scale up as the number of photon packets to be simulated increases.

## 6. Computation Results of mcml and Verification

Some computation results are described in this chapter as examples, and some of them are compared with the results from other theory or with the Monte Carlo simulation results from other investigators to verify the program.

### 6.1 Total diffuse reflectance and total transmittance

We computed the total diffuse reflectance and total transmittance of a slab of turbid medium with the following optical properties: relative refractive index  $n = 1$ , absorption coefficient  $\mu_a = 10 \text{ cm}^{-1}$ , scattering coefficient  $\mu_s = 90 \text{ cm}^{-1}$ , anisotropy factor  $g = 0.75$ , and thickness  $d = 0.02 \text{ cm}$ . Ten Monte Carlo simulations of 50,000 photon packets each are completed. Then, the averages and the standard errors of the total diffuse reflectance and total transmittance are computed (Table 6.1). The table also lists the results from van de Hulst's table (van de Hulst, 1980) and from Monte Carlo simulations by Prahl *et al.* (1989). All results agree with each other.

**Table 6.1.** Verification of the total diffuse reflectance and the total transmittance in a slab with a matched boundary.

Source	$R_d$ Average	$R_d$ Error	$T_t$ Average	$T_t$ Error
van de Hulst, 1980	0.09739		0.66096	
mcml	0.09734	0.00035	0.66096	0.00020
Prahl <i>et al.</i> , 1989	0.09711	0.00033	0.66159	0.00049

The columns " $R_d$  Average" and " $R_d$  Error" are the average and the standard error of the total diffuse reflectance respectively, while the columns " $T_t$  Average" and " $T_t$  Error" are the average and the standard error of the total transmittance.

For a semi-infinite turbid medium that has mismatched refractive index with the ambient medium, the average and the standard error of the total diffuse reflectance are computed similarly, and compared in Table 6.2 with Giovanelli's (1955) results and Monte Carlo simulation results by Prahl *et al.* (1989). The medium has the following optical properties: relative refractive index  $n = 1.5$ ,  $\mu_a = 10 \text{ cm}^{-1}$ ,  $\mu_s = 90 \text{ cm}^{-1}$ ,  $g = 0$  (isotropic scattering). Ten Monte Carlo simulations of 5,000 photon packets each are completed to compute the average and the standard error of the total diffuse reflectance.

**Table 6.2.** Verification of the total diffuse reflectance in a semi-infinite medium with a mismatched boundary.

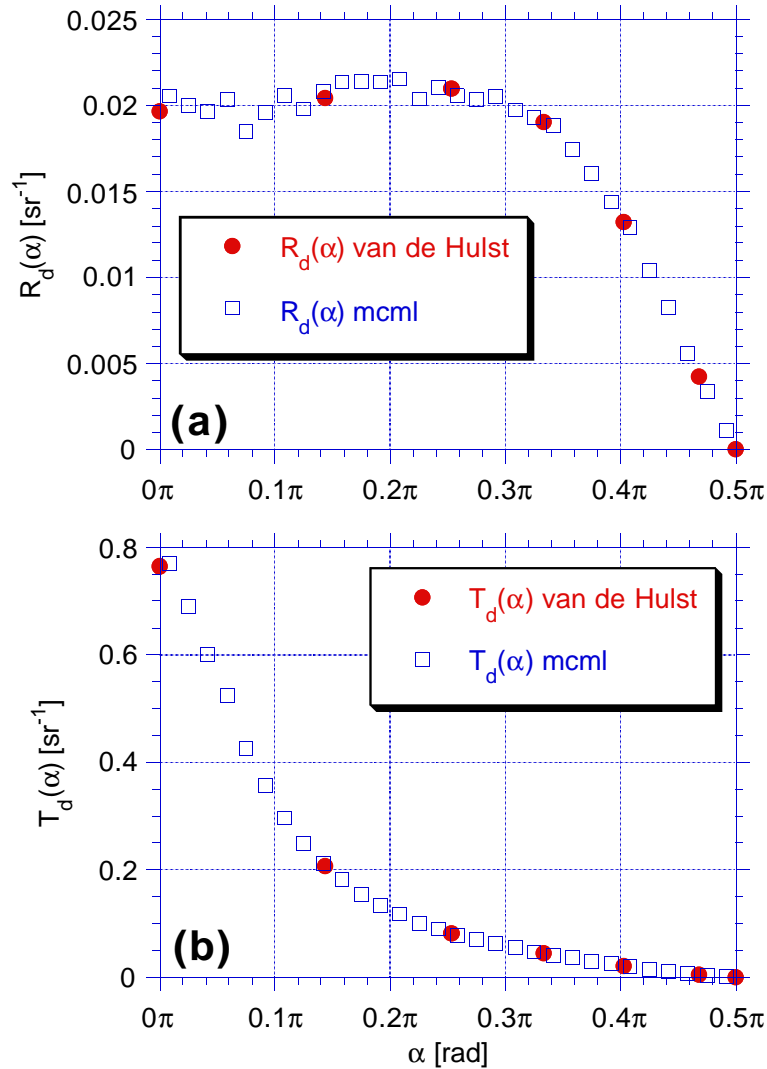
Source	$R_d$ Average	$R_d$ Error
Giovanelli, 1955	0.2600	
mcml	0.25907	0.00170
Prahl <i>et al.</i> , 1989	0.26079	0.00079

## **6.2 Angularly resolved diffuse reflectance and transmittance**

We used mcml to compute the angularly resolved diffuse reflectance and transmittance of a slab of turbid medium with the following optical properties: relative refractive index  $n = 1$ , absorption coefficient  $\mu_a = 10 \text{ cm}^{-1}$ , scattering coefficient  $\mu_s = 90 \text{ cm}^{-1}$ , anisotropy factor  $g = 0.75$ , and thickness  $d = 0.02 \text{ cm}$ . In the simulation, 500,000 photon packets are used, and the number of angular grid elements is 30. The results are compared with the data from van de Hulst's table (van de Hulst, 1980) as shown in Figs. 6.2a and b.

Since mcml also scores the unscattered transmittance into the transmittance array, we have to subtract it from the first element of the array to obtain the diffuse transmittance. In this case, the unscattered transmittance is  $\exp(-(\mu_a + \mu_s) d) = \exp(-2) \approx 0.13534$ , which is only scored into the first grid element in the  $\alpha$  direction. The solid angle spanned by the first grid element is  $\Delta\Omega \approx 2 \pi \sin(\Delta\alpha/2) \Delta\alpha$ , where  $\Delta\alpha = \pi/(2 \times 30)$ . Therefore, the contribution of the unscattered transmittance to the first element of the array  $T_t(\alpha)$  is  $\exp(-2)/\Delta\Omega \approx 15.68$ . After the subtraction, we get the adjusted first element of transmittance array being  $0.765 \text{ sr}^{-1}$ , which is the diffuse transmittance. Note that the variance in Fig. 6.2a for diffuse reflectance is larger than that in Fig. 6.2b for diffuse transmittance. This is because the total diffuse reflectance is much less than the total diffuse transmittance ( $0.09739$  vs  $0.66096 - 0.13534 = 0.52562$ , as shown in Table 6.1).

Since van de Hulst used a different definition of reflectance and transmittance, and a normalization to incident flux  $\pi$ , we multiplied van de Hulst's data by the cosine of the exiting angle from the normal to the surface, then divided by  $\pi$ .

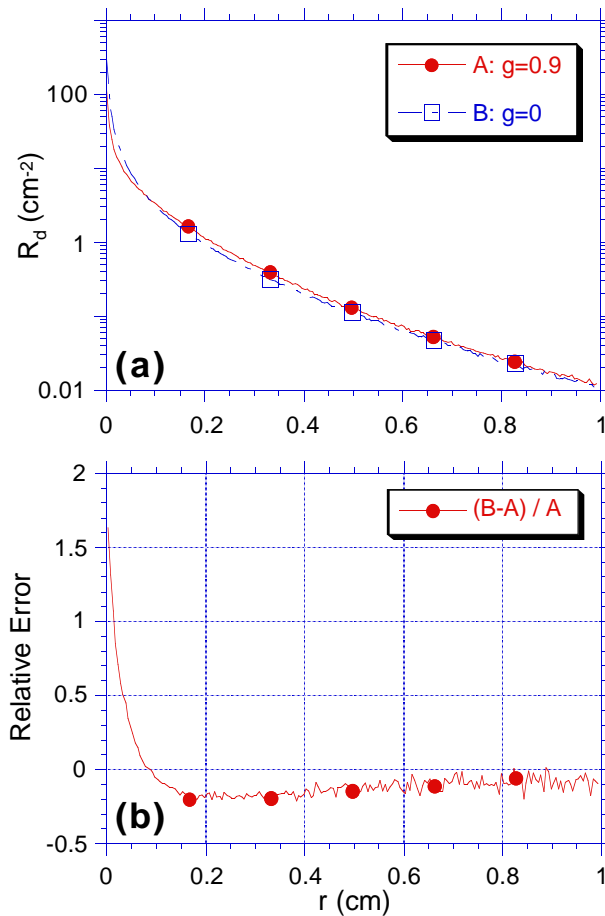


**Fig. 6.2.** Angularly resolved (a) diffuse reflectance  $R_d(\alpha)$  and (b) diffuse transmittance  $T_d(\alpha)$  vs the angle between the photon exiting direction and the normal to the medium surface  $\alpha$ . Solid circles are from van de Hulst's table, and the open square boxes are from mcml simulation. The optical parameters are: relative refractive index  $n = 1.0$ ,  $\mu_a = 10 \text{ cm}^{-1}$ ,  $\mu_s = 90 \text{ cm}^{-1}$ ,  $g = 0$ , thickness  $d = 0.02 \text{ cm}$ .

### 6.3 Radially resolved diffuse reflectance

As an example of the simulation of radially resolved diffuse reflectance, we compare the diffuse reflectances of two semi-infinite media whose optical properties are

governed by similarity relations (Wyman *et al.*, 1989a and 1989b). The two sets of optical parameters share the same absorption coefficient  $\mu_a$  and transport scattering coefficient  $\mu_s(1-g)$ . These two media should give approximately the same diffuse reflectances if the similarity relations are valid. The results (Fig. 6.3) confirmed that the similarity relations do not apply for photon sources near the media boundary as Wyman *et al.* expected. The relative difference between two diffuse reflectances is very large when the radius  $r$  is small, and becomes smaller when  $r$  becomes larger. We have also confirmed that the similarity relations work very well when the photon source is deep inside the media using a modified mcml (see Chapter 11).



**Fig. 6.3.** (a) Comparison and (b) the relative difference of diffuse reflectances as a function of radius  $r$  for two semi-infinite media whose optical properties are "equivalent" according to similarity relations.

In Fig. 6.3., The optical properties for curve A are:  $\mu_a = 0.1 \text{ cm}^{-1}$ ,  $\mu_s = 100 \text{ cm}^{-1}$ ,  $g = 0.9$ ,  $n_{\text{rel}} = 1$ , and the optical properties for curve B are:  $\mu_a = 0.1 \text{ cm}^{-1}$ ,  $\mu_s = 10 \text{ cm}^{-1}$ ,  $g = 0$ ,  $n_{\text{rel}} = 1$ . The two curves A and B are results from pure Monte Carlo simulations of 1 million photon packets. The grid line separation in the  $r$  direction is 0.005 cm, and number of grid elements is 200.

#### **6.4 Depth resolved internal fluence**

As an example of simulation of the depth resolved internal fluence, we show the results for two semi-infinite media with matched and mismatched boundaries respectively

(Fig. 6.4). The dimensionless internal fluence as a function of depth  $z$ ,  $\phi_z[i_z]$  in Section 4.2, is computed from the response to an infinitely narrow photon beam normally incident on a semi-infinite medium. However, it can be equivalently considered as the response of an infinitely wide photon beam perpendicularly incident on a semi-infinite medium with a difference of a constant  $S$  (see Section 4.2), where  $S$  is the power density. Since the direction output of the program mcml gives  $A_z[i_z]$  instead of  $\phi_z[i_z]$ , we divided  $A_z[i_z]$  by the absorption coefficient of the semi-infinite medium to get  $\phi_z[i_z]$ . Although the response of an infinitely narrow photon beam is dimensionless (Fig. 6.4), if the input photon beam is measured in  $\text{W}/\text{cm}^2$  or  $\text{J}/\text{cm}^2$  as the power density or energy density, the unit of fluence is also in the unit of  $\text{W}/\text{cm}^2$  or  $\text{J}/\text{cm}^2$  correspondingly. Since we only consider steady-state responses, we can discuss either energy density or power density because they can be converted back and forth.

Note that the fluence near the surface is larger than 1 because the back scattered light augments the fluence. Furthermore, the internal fluence for the medium with a mismatched boundary is higher than that for the medium with a matched boundary. This is due to the internal reflection by the mismatched boundary, therefore the photons that would escape from the boundary of the boundary-matched medium may be reflected back into the medium by the mismatched boundary and hence have a greater chance to be absorbed. Also note that when  $z$  is sufficiently deep, the two curves are parallel. This confirms the valid range of diffusion theory. For  $z$  larger than the penetration depth  $\delta$ , diffusion theory predicts that the internal fluence distribution should be (Wilson *et al.*, 1990):

$$\phi(z) = \phi_0 k \exp(-z/\delta) \quad (6.1)$$

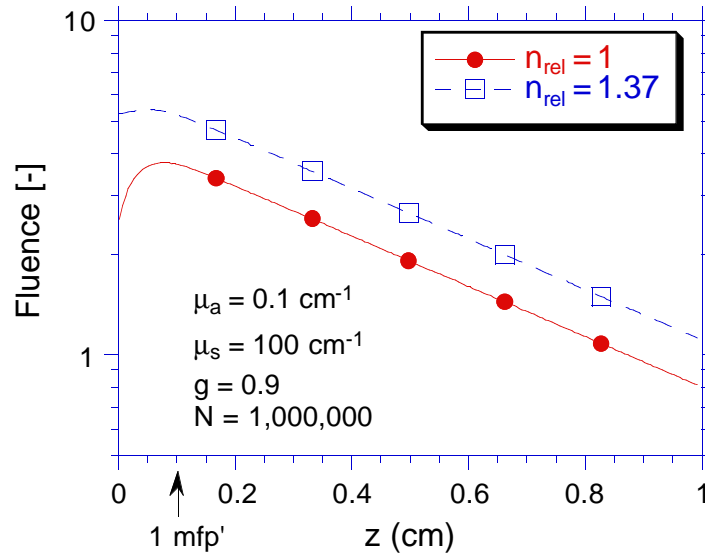
where  $k$  is a scalar that depends on the amount of back scattered reflectance, and  $\phi_0$  is the incident irradiance, which is 1 in our mcml simulation. The scalar  $k$  is obviously a function of the relative index of refraction. Therefore, the matched boundary and the mismatched boundary will have different  $k$ . The penetration depth  $\delta$  is computed:

$$\delta = 1/\sqrt{3 \mu_a (\mu_s + \mu_s (1-g))} = 1/\sqrt{3(0.1)(0.1+100(1-0.9))} \approx 0.57 \text{ cm} \quad (6.2)$$

which is independent of relative index of refraction. Therefore, the two curves in Fig. 6.4 should be off just by a factor due to different  $k$  values when  $z > \delta$ , which means the curves are parallel in log-linear scale when  $z > \delta$ . The two curves shown here are parallel even when  $z > 1 \text{ mfp}' = 1/(\mu_s + \mu_s (1-g)) \approx 0.1 \text{ cm}$ , where  $\text{mfp}'$  is the transport mean free path. One  $\text{mfp}'$  may be a better criterion for valid application of diffusion theory than the



penetration depth. Further supporting evidence can be found in Chapter 11 and Wang *et al.* (1992).



**Fig. 6.4.** Comparison of internal fluences as a function of depth  $z$  for two semi-infinite media with a matched boundary and a mismatched boundary respectively. The results are from Monte Carlo simulations with 1 million photon packets each using mcml. The grid line separation in the  $z$  direction is 0.005 cm, and number of grid elements is 200.

We fit the parallel part of the two curves with exponential functions. The damping constants for the curves are approximately  $1.73 \text{ cm}^{-1}$  for the matched boundary and  $1.74 \text{ cm}^{-1}$  for the mismatched boundary respectively. The reciprocals of the damping constants are 0.578 cm for the matched boundary and 0.575 cm for the mismatched boundary respectively. They are very close to the penetration depth (0.57 cm, Eq. 6.2) predicted from diffusion theory.

### **6.5 Computation times vs optical properties**

We completed multiple Monte Carlo simulations with mcml for semi-infinite media with various optical properties, and fitted the user times as a function of the ratio between scattering coefficient and absorption coefficient  $\mu_s/\mu_a$  and anisotropy  $g$ . The situations for media with matched boundaries (relative refractive index is 1) and mismatched boundaries (relative refractive index is not 1) will be presented separately. Note that the user time is

whatever the system allocates to the running of the program, as opposed to the real time which is wall-clock time. In a time-shared system, they need not be the same, and the real time of the same run may not be reproduced depending on the status of the system. In mcml, the user time is reported to the output data file, and the real time is used to predict when the simulation finishes during the simulation.

Before starting multiple mcml simulations for various optical properties, we know that the time required to finish tracing a photon packet is proportional to the number of steps that a photon packet takes until being terminated. According to the rules for photon propagation described in Chapter 3, this number of steps should not be dependent on the absolute values of scattering coefficient  $\mu_s$  and absorption coefficient  $\mu_a$ , but their ratio. Therefore, we keep one of the two parameters constant (e.g.,  $\mu_s = 100 \text{ cm}^{-1}$ ), and vary the other one (e.g.,  $\mu_a$ ).

### Matched boundary

For media with matched boundaries (relative refractive index  $n_{\text{rel}}$  is 1), we finished multiple mcml simulations of 10,000 photon packets each for various absorption coefficients  $\mu_a$  and anisotropy factors while keeping the scattering coefficient  $\mu_s$  fixed to  $100 \text{ cm}^{-1}$ . The results are listed in Table 6.3, where the ratios between the scattering coefficient and the absorption coefficient are tabulated, instead of the two coefficients themselves separately, and the user

**Table. 6.3.** Computation times for various media with matched boundaries. The column "Predicted User Time" is the computed values using Eqs. 6.1-6.3 presented later. The column "Error" is equal to  $(\text{Predicted User Time} - \text{User Time})/(\text{User Time}) * 100$ .

$\mu_s/\mu_a$	g	User Time (sec./1000 photons)	Predicted User Time (sec./1000 photons)	Error (%)
0.2	0	0.43	0.36	-16.15
1	0	0.78	0.81	3.58
2	0	1.10	1.15	4.42
10	0	2.59	2.56	-0.99
20	0	3.66	3.62	-0.97
100	0	8.46	8.10	-4.23
200	0	12.27	11.46	-6.64
1000	0	29.61	25.61	-13.49
0.2	0.1	0.40	0.38	-5.04
1	0.1	0.80	0.86	7.19
2	0.1	1.10	1.22	10.70
10	0.1	2.80	2.75	-1.82
20	0.1	3.90	3.90	0.10
100	0.1	9.80	8.81	-10.07
200	0.1	13.20	12.52	-5.19
1000	0.1	28.60	28.25	-1.21
0.2	0.5	0.50	0.45	-9.54
1	0.5	1.00	1.08	7.71
2	0.5	1.40	1.57	11.80
10	0.5	3.50	3.73	6.49
20	0.5	5.30	5.42	2.19
100	0.5	12.10	12.90	6.60
200	0.5	17.90	18.74	4.71
1000	0.5	40.60	44.63	9.93
0.2	0.9	0.50	0.49	-1.83
1	0.9	1.20	1.35	12.74
2	0.9	1.90	2.09	10.20
10	0.9	6.30	5.77	-8.39
20	0.9	9.80	8.93	-8.86
100	0.9	25.80	24.62	-4.58
200	0.9	38.10	38.10	0.00
1000	0.9	95.30	105.02	10.20
0.2	0.99	0.50	0.42	-16.18
1	0.99	1.20	1.42	18.68
2	0.99	2.10	2.41	14.85
10	0.99	8.80	8.20	-6.87
20	0.99	16.50	13.88	-15.89
100	0.99	60.60	47.16	<b>-22.18</b>
200	0.99	97.20	79.86	-17.84
1000	0.99	248.80	271.37	9.07

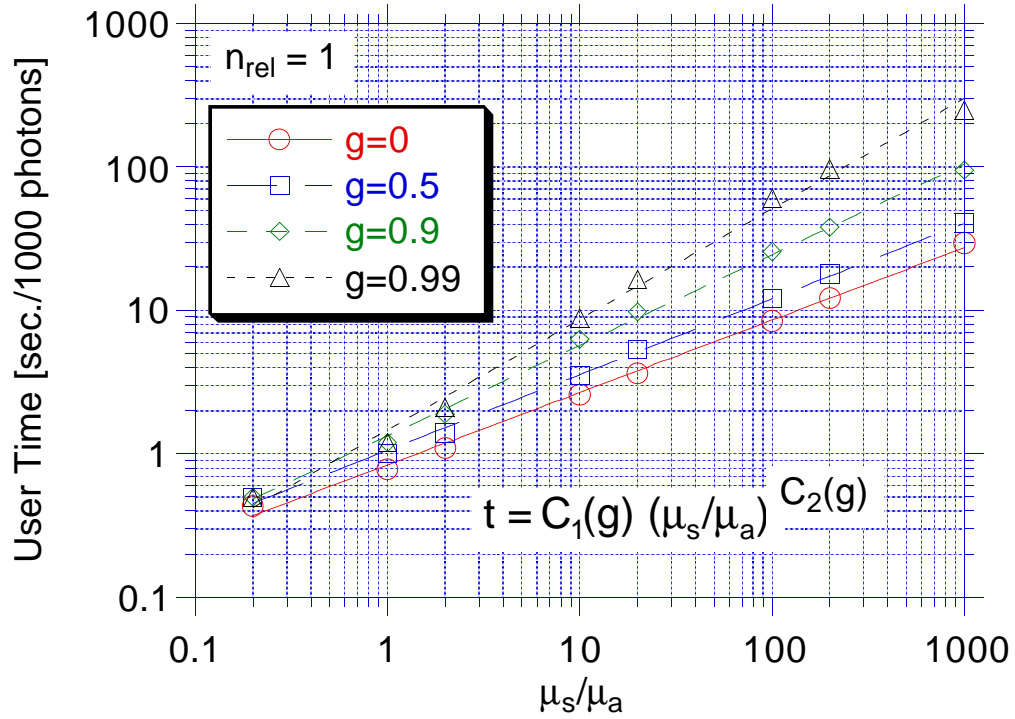
times are converted to seconds per 1000, instead of 10,000, photon packets. The columns "Predicted User Time" and "Error" will be discussed subsequently

We plotted the user times as a function of the ratio between the scattering coefficient and the absorption coefficient for each anisotropy factor  $g$  in a log-log scale (Fig. 6.5). For each anisotropy factor  $g$ , the higher the ratio between the scattering coefficient and the absorption coefficient, the longer the user time. This is because the photon packets in media of higher ratio  $\mu_s/\mu_a$ , compared with media of lower ratio, can jump more steps before reaching the threshold weight and hence having a chance to be terminated. Therefore, the Monte Carlo simulation of low absorbing medium is very slow. If the diffuse reflectance as a function of  $r$  in a low absorption semi-infinite turbid medium is the only physical quantity to be computed, a hybrid model of pure Monte Carlo simulation and diffusion theory (Wang *et al.*, 1992) is a much faster model than pure Monte Carlo simulations. The speed of the hybrid model is not so sensitive to the ratio between the scattering coefficient and the absorption coefficient.

For the same ratio between the scattering coefficient and the absorption coefficient, the larger the anisotropy factor  $g$ , the longer the user time. This is because that the photon packets in media of larger anisotropy factors  $g$  have less chance to be reflected out of the media because the scatterings are more forward directed, and hence to be terminated.

For each anisotropy factor  $g$ , the data points are well aligned in the log-log plot. This means that we can fit the data points for each anisotropy factor  $g$  with a power function. The fitted lines are presented in Fig. 6.5.

The two fitting coefficients  $C_1(g)$  and  $C_2(g)$  are dependent on the anisotropy factor  $g$ . The fitting coefficients  $C_1(g)$  are plotted against the anisotropy factor  $g$  in a log-linear scale (Fig. 6.6a), and can be fitted with an exponential function. Similarly, the fitting coefficients  $C_2(g)$  are plotted against  $(1 - g)$  in a linear-log scale (Fig. 6.6b), and can be fitted with a logarithmic function. These three fittings are summarized as the following empirical formulas:



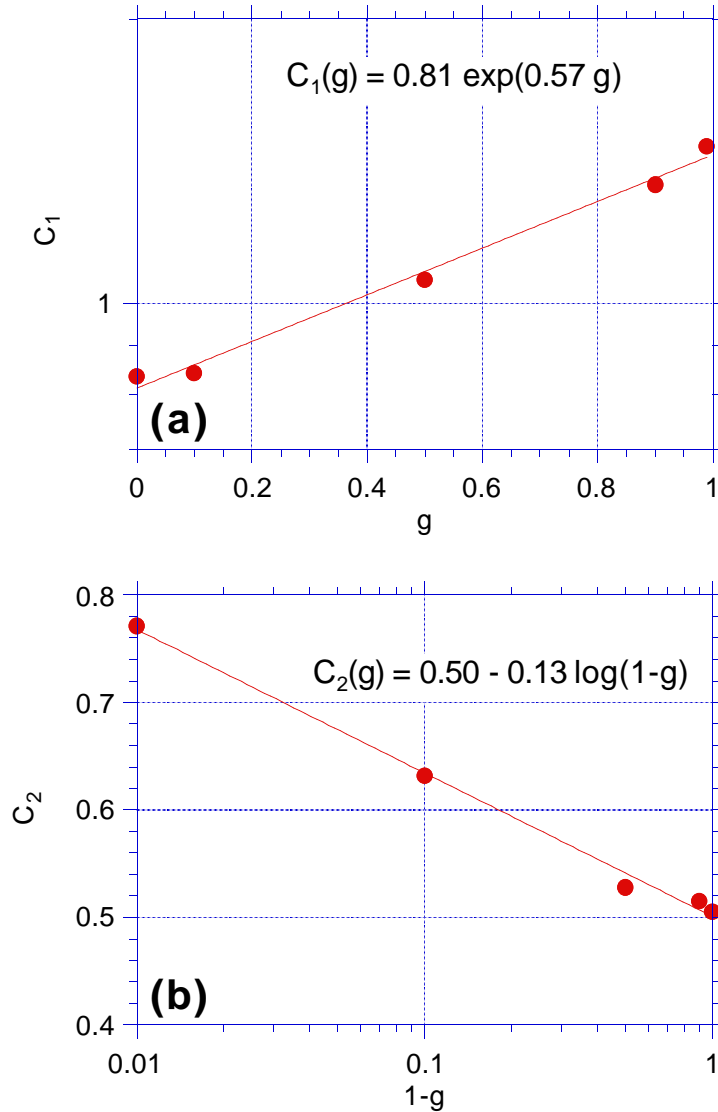
**Fig. 6.5.** The user times vs the ratio between the scattering coefficient  $\mu_s$  and the absorption coefficient  $\mu_a$  for different anisotropy factors  $g$  of media with matched boundaries.

$$C_1(g) = 0.81 \exp(0.57 g) \quad (6.3)$$

$$C_2(g) = 0.50 - 0.13 \log(1-g) \quad (6.4)$$

$$t = C_1(g) (\mu_s/\mu_a)^{C_2(g)} \quad [\text{sec./1000 photons}] \quad (6.5)$$

where  $t$  is the user time in seconds per 1000 photon packets for semi-infinite media with matched boundaries.



**Fig. 6.6.** The fitting coefficients (a)  $C_1(g)$  and (b)  $C_2(g)$  vs the anisotropy factor  $g$  of media with matched boundaries.

To test how good Eqs. 6.3-6.5 are, we use them to compute the user times for the optical properties given in Table 6.3, and presented the computed user times in Table 6.3 as the column "Predicted User Time". The relative errors are within 20% as shown in the column "Error" in Table 6.3 for all rows in the table except one of them (in bold face).

The Eqs. 6.3-6.5 can be used generally to predict user time of a medium with a matched boundary. However, several limitations and notes have to be mentioned. First,

the anisotropy factor  $g$  is limited to less than 0.99, and the accuracy is unknown for  $g > 0.99$  because the fitting coefficient  $C_2(g)$  approaches infinity when  $g$  approaches 1. Second, these equations are based on mcml simulations on a Sun SPARCstation 2. Therefore, we expect a scale factor for Eq. 6.5 or the values in Table 6.3 on a different computer system. This scale factor can be determined by simulating one or several media with optical properties in Table 6.3 using mcml running on your computer system and taking the ratio between the user time on your machine and the user time in Table 6.3. Third, the speed of mcml is related to the threshold weight in the program mcml (WEIGHT in Table 5.1), which is normally  $1 \times 10^{-4}$  (See Table 5.1), and the chance of surviving a roulette (CHANCE in Table 5.1), which is normally 0.1 (See Table 5.1). If these two parameters are changed, Eqs. 6.3-6.5 are no longer valid. It is unexplored yet how these two parameters will affect the user times.

### Mismatched boundary

We repeat the above process to media with mismatched boundaries (relative refractive index  $n_{\text{rel}} \neq 1$ ). We finished multiple mcml simulations of 1,000 (instead of 10,000 for matched boundaries) photon packets each for various absorption coefficients and anisotropy factors while keeping the scattering coefficient fixed to  $100 \text{ cm}^{-1}$  and the relative refractive index to 1.37, which is typical for human tissues in visible or infrared wavelength. The results are listed in Table 6.4.

We plotted the user times as a function of the ratio between the scattering coefficient and the absorption coefficient for each anisotropy factor  $g$  in a log-log scale (Fig. 6.7). Then, the fitting coefficients  $C_1(g)$  and  $C_2(g)$  are plotted with respect to  $g$  and  $(1-g)$  respectively (Fig. 6.8a and b), and fitted with an exponential function and a logarithmic function correspondingly. The fittings give the following empirical formulas:

**Table 6.4.** Computation times for various media with mismatched boundaries. The column "Predicted User Time" is the computed values using Eqs. 6.4-6.6 presented later. The column "Error" is equal to  $(\text{Predicted User Time} - \text{User Time})/(\text{User Time}) * 100$ .

$\mu_s/\mu_a$	g	User Time (sec./1000 photons)	Predicted User Time (sec./1000 photons)	Error (%)
0.2	0	0.48	0.43	-9.74
1	0	0.98	1.05	7.14
2	0	1.42	1.54	8.26
10	0	3.67	3.73	1.51
20	0	5.47	5.45	-0.28
100	0	13.43	13.22	-1.57
200	0	18.67	19.35	3.66
1000	0	50.50	46.90	-7.13
0.2	0.1	0.50	0.44	-11.03
1	0.1	1.00	1.09	8.85
2	0.1	1.50	1.60	6.68
10	0.1	3.83	3.92	2.23
20	0.1	5.90	5.76	-2.44
100	0.1	15.95	14.08	-11.70
200	0.1	22.55	20.71	-8.18
1000	0.1	42.38	50.66	19.54
0.2	0.5	0.53	0.49	-8.10
1	0.5	1.13	1.26	11.25
2	0.5	1.73	1.89	9.31
10	0.5	4.87	4.88	0.22
20	0.5	7.63	7.34	-3.77
100	0.5	19.53	18.95	-2.97
200	0.5	27.08	28.51	5.28
1000	0.5	77.96	73.58	-5.62
0.2	0.9	0.55	0.49	-11.64
1	0.9	1.27	1.45	14.31
2	0.9	2.03	2.33	14.58
10	0.9	7.28	6.95	-4.55
20	0.9	12.10	11.13	-7.99
100	0.9	35.98	33.26	-7.56
200	0.9	55.05	53.28	-3.21
1000	0.9	133.06	159.18	19.63
0.2	0.99	0.55	0.41	<b>-25.96</b>
1	0.99	1.28	1.50	17.16
2	0.99	2.10	2.63	<b>25.19</b>
10	0.99	8.82	9.68	9.77
20	0.99	16.82	16.97	0.92
100	0.99	69.55	62.51	-10.12
200	0.99	120.56	109.60	-9.09
1000	0.99	366.45	403.62	10.14

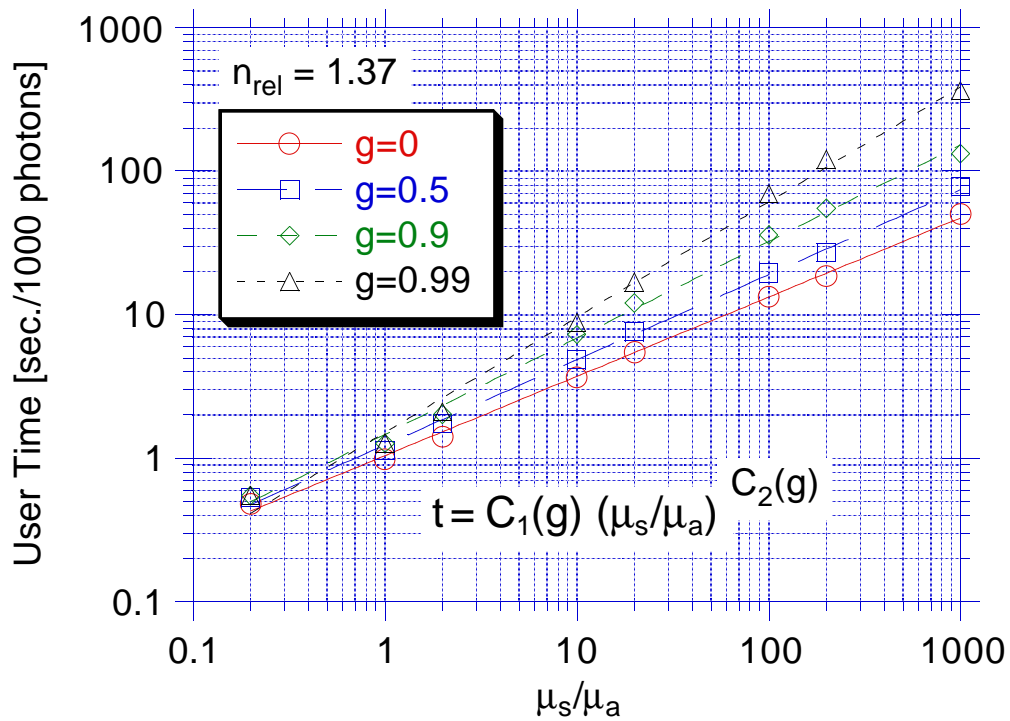


$$C_1(g) = 1.05 \exp(0.36 g) \quad (6.6)$$

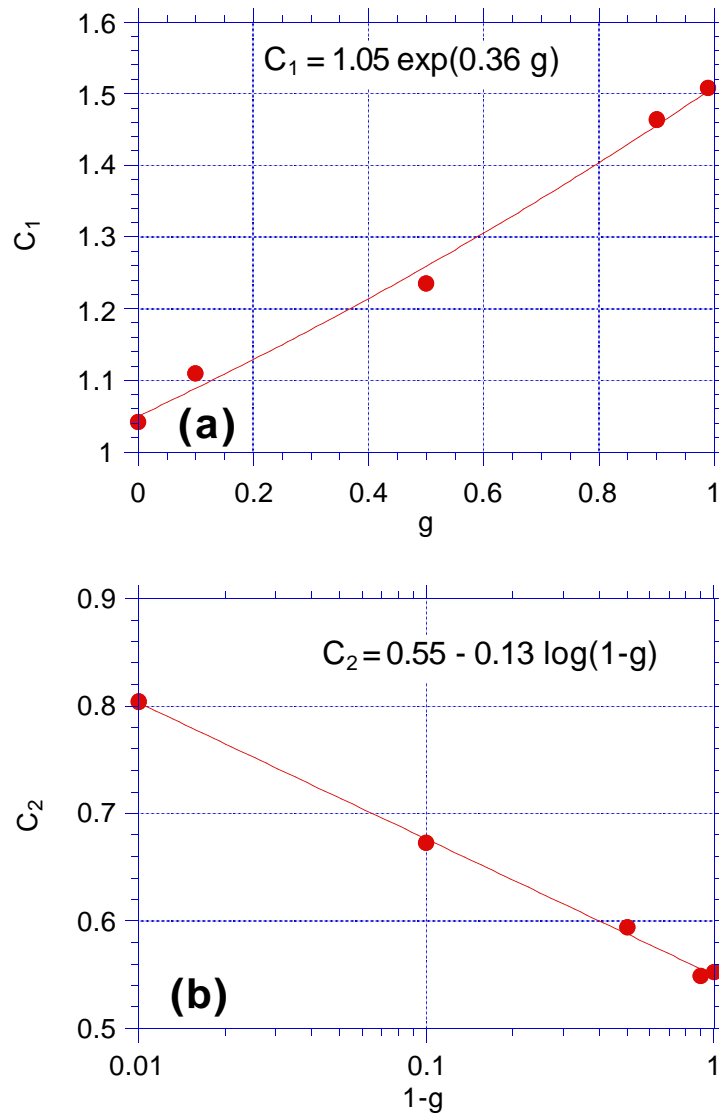
$$C_2(g) = 0.55 - 0.13 \log(1-g) \quad (6.7)$$

$$t = C_1(g) (\mu_s/\mu_a) C_2(g) \quad [\text{sec./1000 photons}] \quad (6.8)$$

where  $t$  is the user time in seconds per 1000 photon packets for semi-infinite media with mismatched boundaries ( $n_{\text{rel}} = 1.37$ ).



**Fig. 6.7.** The user times vs the ratio between the scattering coefficient  $\mu_s$  and the absorption coefficient  $\mu_a$  for different anisotropy factors  $g$  in media with relative refractive index 1.37.



**Fig. 6.8.** The fitting coefficients (a)  $C_1$  and (b)  $C_2$  vs the anisotropy factor  $g$  of media with relative refractive index 1.37.

To test how good Eqs. 6.6-6.8 are, we use them to compute the user times for the optical properties in Table 6.4, and presented the computed user times in Table 6.4 in the column "Predicted User Time". For all rows in the table except two of them (in bold face), the relative errors are within 20%. The cautions made for media with matched boundaries apply here as well.

To summarize the empirical formulas for both matched and mismatched boundaries, we list the formulas in Table 6.5.

**Table 6.5.** Empirical formulas of user times for matched and mismatched boundaries.

Items	Matched ( $n_{rel} = 1$ )	Mismatched ( $n_{rel} = 1.37$ )
$C_1(g)$	$0.81 \exp(0.57 g)$	$1.05 \exp(0.36 g)$
$C_2(g)$	$0.50 - 0.13 \log(1-g)$	$0.55 - 0.13 \log(1-g)$
$t$ [sec./1000 photons]	$C_1(g) (\mu_s/\mu_a) C_2(g)$	$C_1(g) (\mu_s/\mu_a) C_2(g)$

## 6.6 Scored Physical Quantities of Multi-layered Tissues

For multi-layered tissues, we have not found computation results based on other theories to compare with our computation. However, thanks to Gardner's cooperation (Gardner *et al.*, 1992), we compared our Monte Carlo simulation results of multi-layered tissues with their results of an independently written Monte Carlo simulation. The comparison includes the diffuse reflectance versus radius,  $R_d(r)$ , where the radius  $r$  is the distance between the photon incident point and the observation point, the transmittance versus radius,  $T_t(r)$ , and the internal fluence versus  $z$ ,  $\phi_z(z)$ , and the internal fluence versus  $r$  and  $z$ ,  $\phi_{rZ}(r, z)$ . This comparison can at least greatly reduce the chance of programming errors.

We chose a three-layer tissue for the simulation. The optical properties of each layer are shown in Table 6.6.

**Table 6.6.** The optical properties of the three-layer tissue.

Layer	Refractive Index $n$	Absorption Coeff. ( $\text{cm}^{-1}$ )	Scattering Coeff. ( $\text{cm}^{-1}$ )	Anisotropy Factor $g$	Thickness (cm)
1	1.37	1	100	0.9	0.1
2	1.37	1	10	0	0.1
3	1.37	2	10	0.7	0.2

The refractive indices of the top and bottom ambient media are both set to 1.0. The grid separations in  $z$  and  $r$  directions are both 0.01 cm. The number of grid elements in  $z$

and r directions are 40 and 50 respectively. We do not want to resolve the exiting angles of reflected or transmitted photons, therefore we set the number of grid elements in the angle  $\alpha$  direction to 1. The number of photon packets traced is 1,000,000. The actual input file for the program mcml is as follows.

```

1.0                               # file version
1                               # number of runs

### Specify data
comp.mco      A                 # output filename, ASCII/Binary
1000000      # No. of photons
.01 .01      # dz, dr
40  50  1    # No. of dz, dr & da.

3                               # No. of layers
# n   mua   mus   g     d      # One line for each layer
1.0   # n for medium above.
1.37  1     100   0.90  0.1    # layer 1
1.37  1     10    0     0.1    # layer 2
1.37  2     10    0.70  0.2    # layer 3
1.0   # n for medium below.

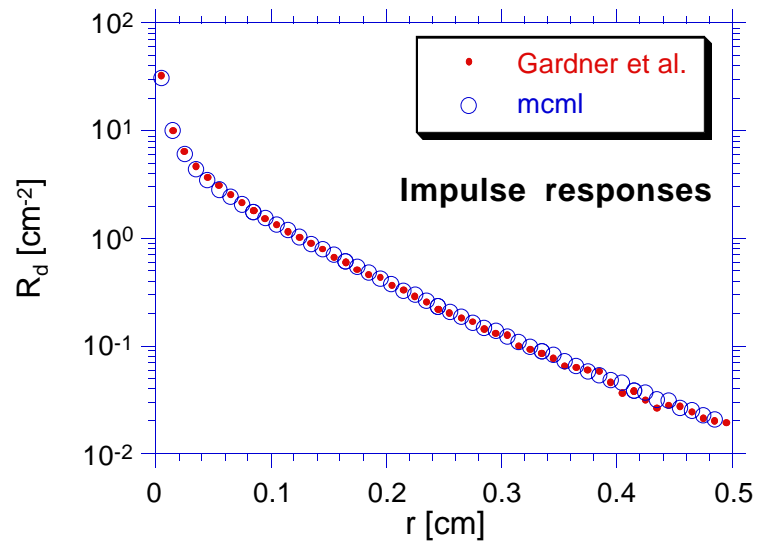
```

Craig Gardner set up the same run for his simulation code except he used only 100,000 photons (Gardner *et al.*, 1992). The total diffuse reflectance and transmittance from the two simulations are compared in Table 6.7.

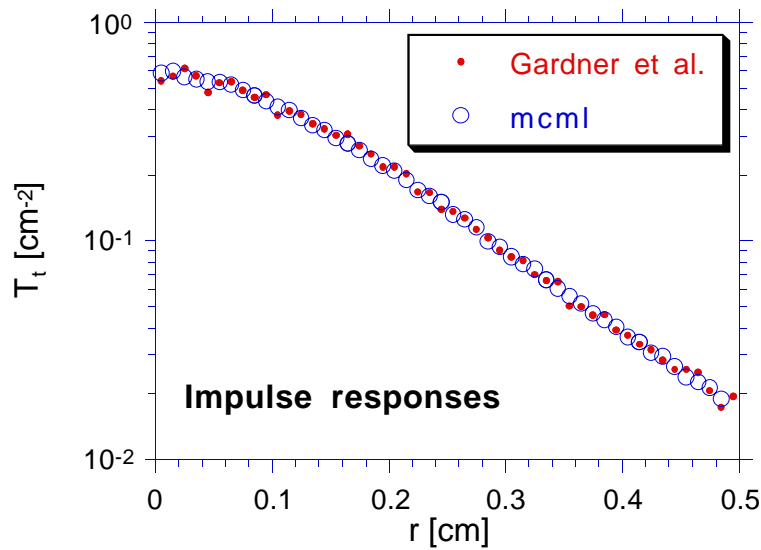
**Table 6.7.** Comparison of total diffuse reflectances and transmittances.

Source	Diffuse Reflectance $R_d$	Transmittance $T_t$
Gardner <i>et al.</i> , 1992	0.2381	0.0974
mcml	0.2375	0.0965

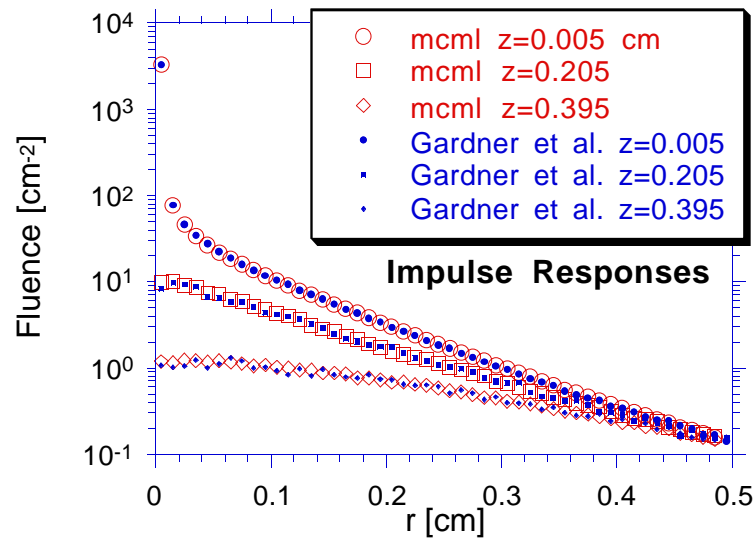
The comparison between the diffuse reflectances and transmittances are shown in Figs. 6.9 and 6.10 respectively. The comparison between fluences  $\phi_{rz}(r, z)$ , as an impulse response, as a function of radius  $r$  for several given  $z$  coordinates is shown in Fig. 6.11. The comparison between fluences  $\phi_z(z)$  as a function of  $z$  as described in Section 4.2 is subsequently given in Fig. 6.12. All of the comparisons have shown agreement between the two independent simulations.



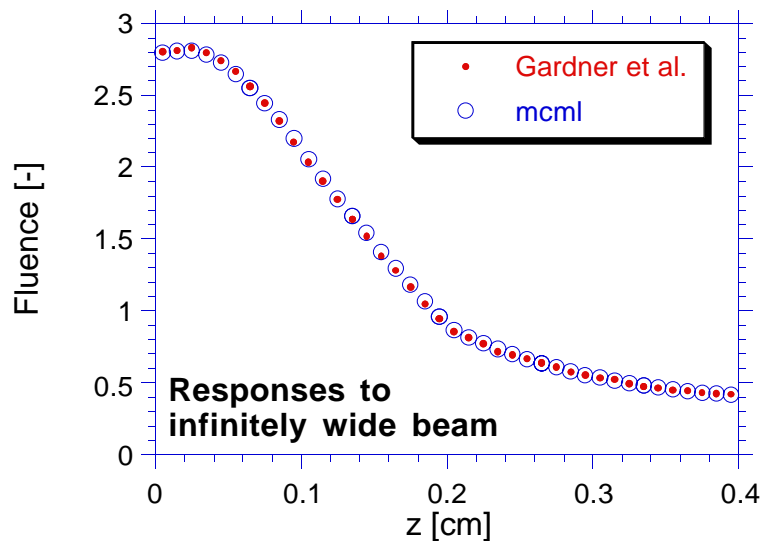
**Fig. 6.9.** Comparison between diffuse reflectances as a function of radius based on Gardner's computation (Gardner *et al.*, 1992) and mcml simulation.



**Fig. 6.10.** Comparison between transmittances as a function of radius based on Gardner's computation (Gardner *et al.*, 1992) and mcml simulation.

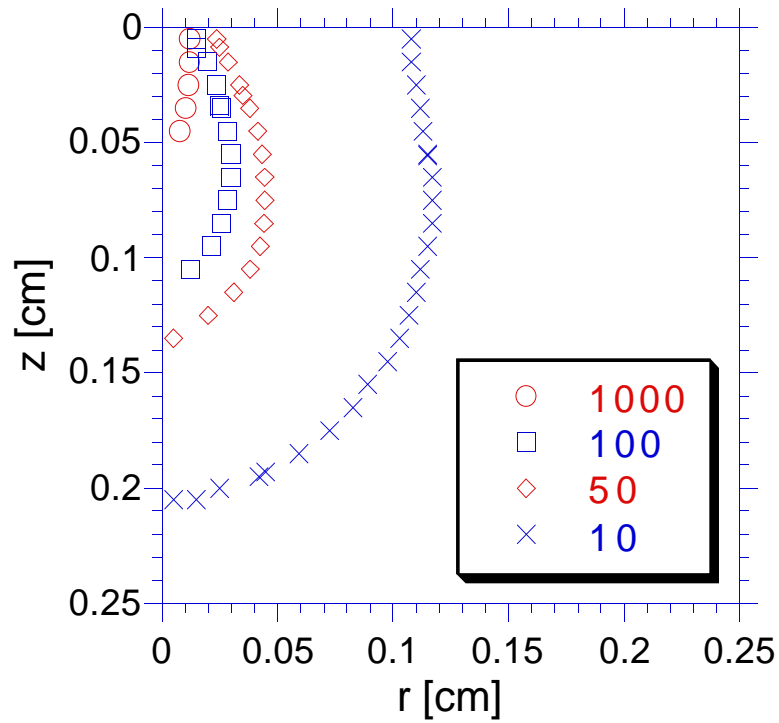


**Fig. 6.11.** Comparison between fluences as a function of radius  $r$  for several  $z$  coordinates based on Gardner's computation (Gardner *et al.*, 1992) and mcml simulation.



**Fig. 6.12.** Comparison between fluences as a function of  $z$  based on Gardner's computation (Gardner *et al.*, 1992) and mcml simulation.

For 2D arrays such as the fluence as a function of  $r$  and  $z$ , `conv` has the ability to output the data in contour format (see Sections 10.9 and 10.10). The fluence as a function of  $r$  and  $z$  of the impulse response is shown in contour lines in Fig. 6.13.



**Fig. 6.13.** Contour plot of the fluence as a function of  $r$  and  $z$  of impulse response based on mcml simulation.

## **7. Convolution for Photon Beams of Finite Size**

This chapter will discuss the principles and implementation of convolving Monte Carlo simulation results for an infinitely narrow photon beam to yield the responses to photon beams of finite size. Gaussian beams and circularly flat beams are considered as special cases.

### **7.1 Principles of convolution**

So far we have only dealt with the response to an infinitely narrow photon beam normally incident on the surface of a multi-layered tissue. This response is also called the impulse response. However, all photon beams have finite size in reality. Theoretically, we can use the Monte Carlo simulation to compute the response to a finite size photon beam directly by distributing the initial positions of the launched photon packets. The only problem is that it requires a larger number of photon packets to be traced to get acceptable variance than simulating the responses of an infinitely narrow photon beam. Therefore, this method is not efficient although sometimes it might be the only approach for some types of tissue configurations which can not be convolved, such as a tissue with an irregular buried object.

Fortunately, the system we are dealing with is linear and invariant. The linearity means that if the input intensity of the infinitely narrow photon beam is multiplied by a factor, the responses will be multiplied by the same factor. It also means that the response to two photon beams is the sum of the responses to each photon beam. The invariance means that when the infinitely narrow photon beam is shifted horizontally by a distance in a certain direction, the responses will be shifted also horizontally by the same distance in the same direction. Therefore, if we assume the photon beam of finite size is collimated, the response of an infinitely narrow photon beam will be a Green's function of the tissue system, and the response of the finite size photon beam can be computed from the convolution of the Green's function according to the profile of the finite size photon beam.

Note that the responses mentioned above can be the internal absorption distribution, or the reflectance or transmittance distributions. We denote the responses generally as  $C(x, y, z)$  although it may not be a three-variable function of all three coordinates. Such degeneracy due to the symmetry will be discussed subsequently. We denote the Green's function corresponding to the type of response under consideration as  $G(x, y, z)$ . Since



the photon beam is normally incident on the tissue surface, the function  $G(x, y, z)$  possesses cylindrical symmetry. If the collimated photon beam as the source has the intensity profile  $S(x, y)$ , the responses can be obtained through convolution (Prahl, 1988; Prahl *et al.*, 1989):

$$C(x, y, z) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} G(x-x', y-y', z) S(x', y') dx' dy' \quad (7.1a)$$

or through variable transformation with  $x'' = x - x'$  and  $y'' = y - y'$ :

$$C(x, y, z) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} G(x'', y'', z) S(x-x'', y-y'') dx'' dy'' \quad (7.1b)$$

In Eq. 7.1a the Green's function is a function of the distance between the source point  $(x', y')$  and the observation point  $(x, y)$ , where the distance is:

$$d' = \sqrt{(x-x')^2 + (y-y')^2} \quad (7.2)$$

If the intensity profile  $S(x', y')$  of the source also has cylindrical symmetry,  $S(x', y')$  is only a function of the radius of the source point  $(x', y')$  with respect to the origin point of the coordinate system, where the radius is:

$$r' = \sqrt{x'^2 + y'^2} \quad (7.3)$$

Therefore, Eq. 7.1a can be reformulated considering these symmetries:

$$C(x, y, z) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} G(\sqrt{(x-x')^2 + (y-y')^2}, z) S(\sqrt{x'^2 + y'^2}) dx' dy' \quad (7.4a)$$

Similarly, Eq. 7.1b can also be reformulated with these symmetries:

$$C(x, y, z) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} G(\sqrt{x''^2 + y''^2}, z) S(\sqrt{(x-x'')^2 + (y-y'')^2}) dx'' dy'' \quad (7.4b)$$

Since the response  $C(x, y, z)$  will have the same cylindrical symmetry, the problem can be more easily handled in a cylindrical coordinate system, where Eqs. 7.4a and 7.4b can be written:

$$C(r, z) = \int_0^{\infty} S(r') r' \left[ \int_0^{2\pi} G(\sqrt{r^2 + r'^2 - 2rr'\cos\theta'}, z) d\theta' \right] dr' \quad (7.5a)$$

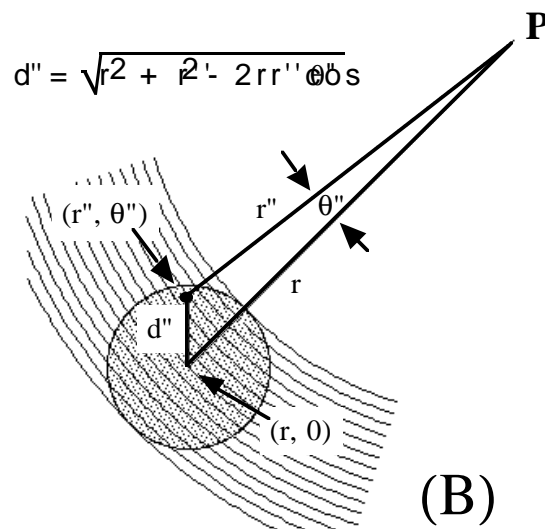
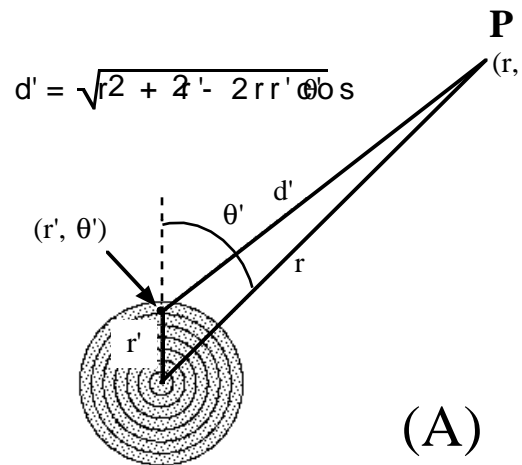
$$C(r, z) = \int_0^{\infty} G(r'', z) r'' \left[ \int_0^{2\pi} S(\sqrt{r^2 + r''^2 - 2rr''\cos\theta''}) d\theta'' \right] dr'' \quad (7.5b)$$

Eq. 7.5b is more advantageous than Eq. 7.5a in computation because the integration over  $\theta''$  is independent of  $z$ . This integration hence need only be computed once for all depths  $z$ . In some cases as presented subsequently, the integral over  $\theta''$  can be expressed analytically, therefore the two-dimensional integral is converted into a one dimensional integral.

The transformation of variables is illustrated in Fig. 7.1. The first coordinate system  $(r', \theta', z)$  has its origin at the center of the source, as in Fig. 7.1A and Eq. 7.5a. The point of observation is at  $(r, 0)$ . An incremental region of source is located at  $(r', \theta')$  and has a value  $S(r')$ . The distance between the source point and the observation point is  $d'$  equal  $\sqrt{r^2 + r'^2 - 2rr'\cos\theta'}$ .

The second coordinate system  $(r'', \theta'', z)$  has its origin at the center of the point of observation, as in Fig. 7.1B and Eq. 7.5b. The source is centered at  $(r, 0)$ . The incremental region of source is located at  $(r'', \theta'')$  and has a value  $S(d'')$ , where  $d''$  equals  $\sqrt{r^2 + r''^2 - 2rr''\cos\theta''}$ . The distance between the source point and the observation point is  $r''$ .

In the following sections, we will consider a Gaussian beam and a circularly flat beam as examples of cylindrical symmetry to further simplify Eq. 7.5b.



**Fig. 7.1.** Illustration of the transform between two coordinate systems. The stippled circle is the laser source and P is the point of observation. The circular lines schematically represent the integration of Eq. 7.5a (A) and Eq. 7.5b (B).

## 7.2 Convolution over Gaussian beams

In the case of a Gaussian beam, if the divergence is ignored, the above convolution can be applied. If the  $1/e^2$  radius of the Gaussian beam is denoted by  $R$ , the beam intensity profile is:

$$S(r') = S_0 \exp(-2 (r'/R)^2) \quad (7.6)$$

where the intensity in the center ( $r=0$ ),  $S_0$ , is related to the total power  $P$  by:

$$S_0 = 2 P / (\pi R^2) \quad (7.7)$$

Substituting Eq. 7.6 into Eq. 7.5b, the convolution becomes:

$$C(r, z) = S(r) \int_0^{\infty} G(r'', z) \exp(-2 (r''/R)^2) \left[ \int_0^{2\pi} \exp(4rr'' \cos\theta''/R^2) d\theta'' \right] r'' dr'' \quad (7.8)$$

The integration in the square brackets resembles the integral representation of the modified Bessel function (Spiegel, 1968):

$$I_0(x) = \frac{1}{2\pi} \int_0^{2\pi} \exp(x \sin\theta) d\theta \quad (7.9a)$$

which can be reformatted to be:

$$I_0(x) = \frac{1}{2\pi} \int_0^{2\pi} \exp(x \cos\theta) d\theta \quad (7.9b)$$

Eq. 7.8 can be written by substituting Eq. 7.9b into it:

$$C(r, z) = S(r) \int_0^{\infty} G(r'', z) \exp(-2 (r''/R)^2) I_0(4rr''/R^2) 2\pi r'' dr'' \quad (7.10)$$

where  $I_0$  is the zero order modified Bessel function.

### 7.3 Convolution over circularly flat beams

If the photon beam is homogeneous within a radius  $R$  and collimated, the source function becomes:

$$S(r') = \begin{cases} P/(\pi R^2) & \text{if } r' \leq R \\ 0 & \text{if } r' > R \end{cases} \quad (7.11)$$

where  $P$  is the total power of the beam. Substituting Eq. 7.11 into Eq. 7.5b, the convolution becomes:

$$C(r, z) = P/(\pi R^2) \int_0^{\infty} G(r'', z) I_{\theta}(r, r'') 2 \pi r'' dr'' \quad (7.12)$$

where the function  $I_{\theta}(r, r'')$  is:

$$I_{\theta}(r, r'') = \begin{cases} 1 & \text{if } R \geq r + r'' \\ \frac{1}{\pi} \cos^{-1}((r^2 + r''^2 - R^2)/(2rr'')) & \text{if } |r - r''| \leq R < r + r'' \\ 0 & \text{if } R < |r - r''| \end{cases} \quad (7.13)$$

From Eq. 7.13 and Fig. 7.1B, the limits of integration in Eq. 7.12 can be changed to a finite region:

$$C(r, z) = P/(\pi R^2) \int_a^{r+R} G(r'', z) I_{\theta}(r, r'') 2 \pi r'' dr'' \quad (7.14a)$$

where

$$a = \text{Max}(0, r - R) \quad (7.14b)$$

where the function  $\text{Max}$  takes the larger of the two arguments.

The circular lines in Fig. 7.1B illustrated the second case in Eq. 7.13 when the observation point  $P$  is outside of the source. When the point  $P$  is outside the source, the first case of Eq. 7.13 is never satisfied. Readers can similarly draw the pictures for the case where the point  $P$  is inside the source. Note that much of the region of integration lies outside the source and therefore the value of  $S$  in the integrand is zero.

As a special case of a circularly flat beam, we let the radius  $R$  approach infinity, which represents an infinitely wide flat beam. In this case the total power  $P$  also

approaches infinity, but we can use the power density to describe the intensity of the beam. The convolution for this case can be accomplished by simply letting  $R \rightarrow \infty$  and  $P/(\pi R^2) \rightarrow S$ , where  $S$  is the power density or irradiance ( $\text{W}/\text{cm}^2$ ), in Eq. 7.14.  $I_\theta(r, r'')$  will be 1 constantly. Eq. 7.14 becomes:

$$C(r, z) = S \int_0^{\infty} G(r'', z) 2 \pi r'' dr'' \quad (7.15)$$

#### **7.4 Numerical solution to the convolution**

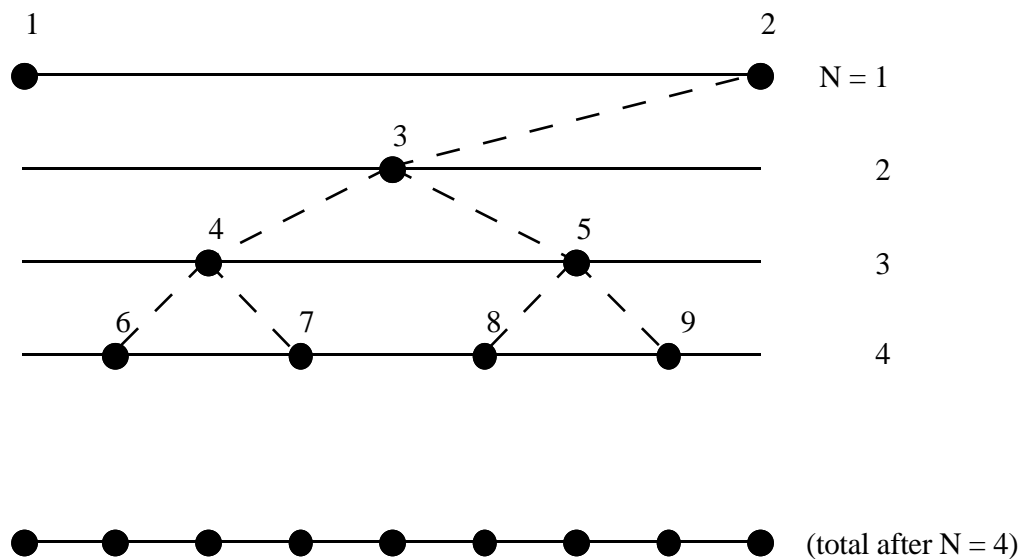
In these two special cases of photon beams, the two-dimensional integrations are converted into one-dimensional integrations, which are significantly faster in numerical computation. Since the Monte Carlo simulation scores physical quantities to discrete grid points, the best choice of integration algorithm is the extended trapezoidal rule, which is written in C called `qtrap()` by Press *et al.* (1988). "Increased sophistication will usually translate into a higher order method whose efficiency will be greater only for sufficiently smooth integrands. `qtrap` is the method of choice, e.g., for an integrand which is a function of a variable that is linearly interpolated between measured data points." Press *et al.* (1988) state.

The simplest choice of the integration is the summation of the integrand values at the original grid points multiplied by the grid separation. However, this approach does not have any control over the integration accuracy. For a given accuracy, sometimes this approach gives more accuracy than required, which is a waste of computation time, and sometimes it gives less accuracy, which does not meet the expectation. For example, the number of original grid elements in the  $r$  direction is 50, and we want to convolve the responses over a circularly flat beam with a radius of  $R$  which is about  $5 \Delta r$ , where  $\Delta r$  is the grid separation in the  $r$  direction. To compute  $C(0, z)$  in Eq. 7.14a, the integral range, from 0 and  $R$ , only covers  $5 \Delta r$ . This means only 5 function evaluations will be completed, which may yield unacceptable answer. On the contrary, the extended trapezoidal rule does the right amount of computation until it reaches the user specified accuracy.

We have slightly modified the original function `qtrap()` so that it takes the required degree of accuracy as an argument. Therefore, the users of the program `conv` can change the allowed error at run time (the program `conv` is to be discussed in the next section).

The sequence of integrand evaluations used in the extended trapezoidal integration is shown in Fig. 7.2. (Press *et al.*, 1988) If we are integrating  $f(x)$  over  $[a, b]$ , we evaluate  $f(a)$  and  $f(b)$  in the first step as noted by 1 and 2 in Fig. 7.2. This step will not give sufficient accuracy unless the function is linear. To refine the grid, we evaluate  $f((a+b)/2)$  in the second step as noted by 3. We continue this process until the integration evaluation reaches the specified accuracy.

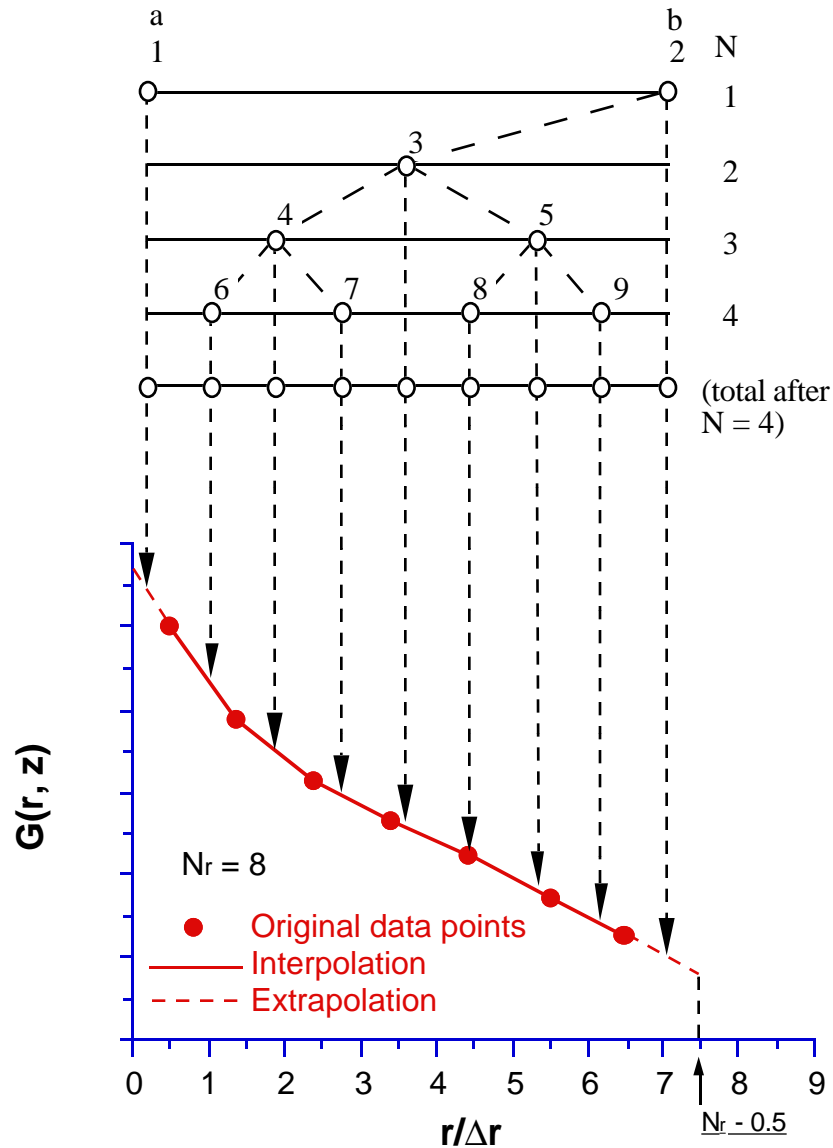
Note that the sequence of integrand evaluation after the third evaluation in Fig. 7.2 resembles a perfectly balanced binary tree. If we want to store the evaluated function values, it is natural to store them in a binary tree for speed retrieval (to be discussed subsequently).



**Fig. 7.2.** Illustration of integrand evaluation sequence in `trapzd()` called by `qtrap()`. "Sequential calls to the routine `trapzd()` incorporate the information from previous calls and evaluate the integrand only at those new points necessary to refine the grid. The bottom line shows the totality of function evaluations after the fourth call." (Press *et al.*, 1988) The sequence of integrand evaluation after the third evaluation resembles a perfectly balanced binary tree.

### Interpolation and extrapolation of physical quantities

As shown in Fig. 7.2, the function  $q_{\text{trap}}()$  will need to evaluate the integrand, hence the physical quantities, at points which may not be the original grid points. Linear interpolations are used for those points that fall between two original grid points. Linear



**Fig. 7.3.** Illustration of the interpolation and extrapolation of the physical quantities. As an example, the number of grid elements in the  $r$  direction  $N_r$  is set to 8.  $\Delta r$  is the grid separation in the  $r$  direction. The integral limits are  $a$  and  $b$  (see Eqs. 7.21 & 7.22). The arrows point to the places where the integrand is evaluated.



extrapolations are used for those points that fall beyond the original grid system. The interpolation and extrapolation are illustrated in Fig. 7.3. The solid circles represent the original score values at the grid points. The solid lines and the dashed lines represent the interpolation and extrapolation respectively. For a given number of grid elements in the  $r$  direction (e.g.,  $N_r = 8$  in this picture), the extrapolation is only computed up to  $(N_r - 0.5)$  because the linear extrapolation can be unreliable for points beyond  $(N_r - 0.5)$ . Therefore, the physical quantity is set to zero beyond  $(N_r - 0.5)$ . Sometimes, the data may be so noisy that the function at the last point is even higher than the function at the second to the last point. In this case, the extrapolation is not used. Instead, we simply set the function values to zero. Note that as we mentioned in the beginning of Chapter 4, the last cells in the  $r$  direction are used to collect the photons that do not fit into the grid system. Therefore, the values in the last cell are usually much higher than the values in the second to the last cells, and hence are not used in the convolution process. In a word, the physical quantities are non-zero in the interval  $[0, r_{\max}]$ , where  $r_{\max}$  is:

$$r_{\max} = (N_r - 0.5) \Delta r \quad (7.16)$$

where  $\Delta r$  is the grid separation in the  $r$  direction.

### Integrand evaluation for Gaussian beams

As shown in Eq. 7.10, the evaluation of the physical quantities is only part of the integrand evaluation for convolution over the Gaussian beam. Although the integration has to converge due to physical reasons, the form of Eq. 7.10 may not be directly computed numerically because the modified Bessel function increases rapidly as the argument increases, and it can exceed the limit which the computer can hold (e.g.,  $10^{+38}$  for some computers). Therefore, a proper reformulation is required to compute Eq. 7.10. We note that the modified Bessel function in the region where the argument is large has the following approximation:

$$I_0(x) \approx \exp(x) / \sqrt{2 \pi x} \quad \text{for large } x \quad (7.17)$$

Therefore, if we extract the exponential term from  $I_0()$ , we can make sure the modified Bessel function decreases as the argument increases. We define the following new function based on  $I_0()$ :

$$I_{0e}(x) = I_0(x) \exp(-x) \quad (7.18a)$$

or

$$I_0(x) = I_{0e}(x) \exp(x) \quad (7.18b)$$

$I_{0e}()$  should always be bounded. Note that Eq. 7.17 is presented just to show the asymptotic behavior of the function  $I_0()$ . Eq. 7.18a by no means carries any approximations. Substituting Eqs. 7.6, 7.7 and 7.18b into Eq. 7.10, it becomes:

$$C(r, z) = \frac{4 P}{R^2} \int_0^{\infty} G(r'', z) \exp[-2 \left(\frac{r''-r}{R}\right)^2] I_{0e}\left(\frac{4rr''}{R^2}\right) r'' dr'' \quad (7.19)$$

Since both the exponential term and the  $I_{0e}()$  term decrease, the integrand can be computed without being out of bound.

Up to now, we have just solved the problem of how to compute the convolution without overflow. However, the computation speed is another issue. We found that the evaluation of the  $\exp() I_{0e}()$  in Eq. 7.19 is a major part of the computation for each integration, which can be up to 90% depending on the specific problem being solved. For multi-variant physical quantities (e.g.,  $A(r, z)$ ), the convolution may repeatedly evaluate the  $\exp() I_{0e}()$  in Eq. 7.19 at the same point as the integration is computed for different  $z$  coordinates.

Therefore, if we can save the function evaluations, i.e. the computations of  $\exp() I_{0e}()$  in Eq. 7.19, for one  $z$  coordinate, then we can save a lot computation time. However, the integration is executed iteratively until a given precision is reached. Hence, the number of function evaluations is unknown in advance. We can only save the function evaluations with dynamic data allocation. Furthermore, since the evaluation sequence of the trapezoidal integration `qtrap()` resembles a binary tree as in Fig. 7.2., a well-balanced binary tree can be used to store the function evaluations for searching speed.

### Integral Limits for Gaussian beams

Since the integral limits in Eq. 7.14a for circularly flat beams are finite, the integration can be computed directly using the function `qtrap()`. In contrast, the upper integral limit in Eq. 7.19 for Gaussian beams is infinity. This problem can be solved using variable transformation and the integration can be computed by the routine `midexp()` (Press *et al.*, 1988). However, we found this approach is not computationally efficient.

We can reduce the upper limit to a finite value by properly truncating the exponential term in Eq. 7.19. When

$$|r'' - r| \leq K R \quad (7.20a)$$

or

$$r - K R \leq r'' \leq r + K R \quad (7.20b)$$

where  $K$  is a constant which can be set in the convolution program `conv`, we compute the integrand, otherwise we think the integrand negligible. For example, if we choose  $K$  equal to 4 (which is actually used in the program), the exponential term in Eq. 7.19 is about  $1 \times 10^{-14}$  whose order of magnitude is considerable larger than the dynamic range of the order of magnitude of the scored physical quantities.

As we discussed in the beginning of this section, we only compute the physical quantities in the interval  $[0, r_{\max}]$ , where  $r_{\max}$  is given by Eq. 7.16. Combining this limit and Eq. 7.20b, Eq. 7.19 becomes:

$$C(r, z) = \frac{4 P}{R^2} \int_a^b G(r'', z) \exp[-2 \left(\frac{r'' - r}{R}\right)^2] I_0 e^{\left(\frac{4 r r''}{R^2}\right)} r'' dr'' \quad (7.21a)$$

$$a = \text{Max}(0, r - K R) \quad (7.21b)$$

$$b = \text{Min}(r_{\max}, r + K R) \quad (7.21c)$$

where the functions `Max()` and `Min()` take the greater and the lesser of the two arguments respectively.

### Integrand evaluation for circularly flat beams

The integrand evaluation for circularly flat beams is much simpler than that for Gaussian beams. However, the evaluation of  $I_0(\theta)$  in Eq. 7.14a is time-consuming. Similar to the integrand evaluation for Gaussian beams, a binary tree is used to store the evaluated  $I_0(\theta)$  to speed up the integration (see the discussion for Gaussian beams).

Integral Limits for circularly flat beams

Since the integral limits in Eq. 7.14a for circularly flat beams are finite, the integration can be computed directly using the function `qtrap()`. As we discussed in the beginning of this section, we only compute the physical quantities in the interval  $[0, r_{\max}]$ , where  $r_{\max}$  is given by Eq. 7.16. Considering this limit, Eq. 7.14a becomes:

$$C(r, z) = P/(\pi R^2) \int_a^b G(r'', z) I_{\theta}(r, r'') 2 \pi r'' dr'' \quad (7.22a)$$

$$a = \text{Max}(0, r - R) \quad (7.22b)$$

$$b = \text{Min}(r_{\max}, r + R) \quad (7.22c)$$

where the functions `Max()` and `Min()` take the greater and the lesser of the two arguments respectively.

Source of error in convolution

In Eqs. 7.21c and 7.22c, the upper limit of the integration may be limited by  $r_{\max}$  which is the grid limit in the  $r$  direction during the Monte Carlo simulation. The physical quantities beyond the original grid limit in the  $r$  direction do not contribute to the convolution, which leads an error.

Let us discuss the case for circularly flat beams first because it is easier. From Eq. 7.22c, we know that when

$$r_{\max} \geq r + R \quad (7.23a)$$

or

$$r \leq r_{\max} - R \quad (7.23b)$$

the limited grid in the  $r$  direction does not affect the convolution. Otherwise, the convolution is truncated by the limited grid in the  $r$  direction. This effect can be see in the next section. Therefore, we should not trust the convolution data for  $r \geq r_{\max} - R$ . In other words, if you want to observe the physical quantity at  $r$  in response to a circularly flat beam of radius  $R$ , the grid limit in the  $r$  direction should be large enough so that Eq. 7.23a holds when you perform the Monte Carlo simulation with `mcml`.

For Gaussian beams, there are no clean formulas like Eqs. 7.23 to describe the valid range because the Gaussian beams theoretically extend to infinity in the  $r$  direction. However, the convolution results of a Gaussian beam with a  $1/e^2$  radius of  $R$  is so close to those of a circularly flat beam with a radius of  $R$  for  $r \gg R$  (shown in the next section). Therefore, we can use the same criteria for circularly flat beams (Eqs. 7.23) for Gaussian beams to certain precision.

The other source of error is due to the Monte Carlo simulation by mcml 1.0. This version of mcml does not score the first interactions separately (see Section 4.3) as Gardner *et al.* (1992b) did. This may make considerable error if the radius of the Gaussian beam is less than three times the grid separation  $\Delta r$ . In other words, the following equation should be satisfied to get reliable convolution:

$$R \geq 3 \Delta r \quad (7.24)$$

In summary, when Eqs. 7.23 and 7.24 hold, the convolution should be reliable.

## **7.5 Computation results of conv and verification**

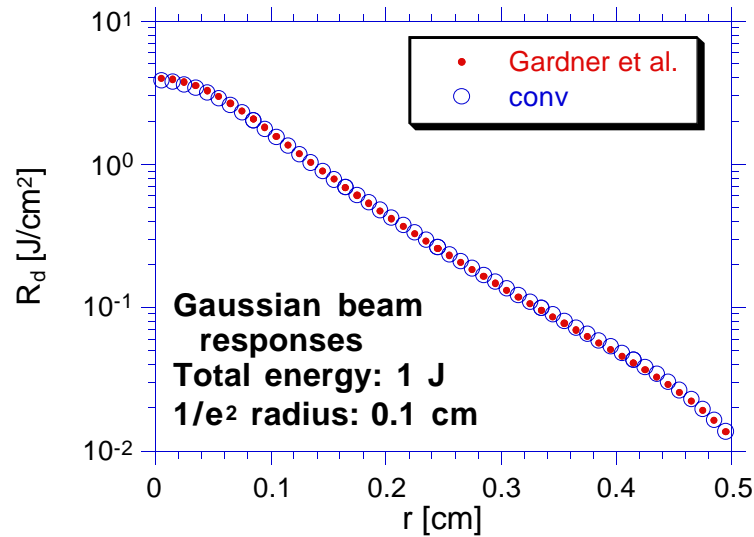
The convolution process of the Monte Carlo simulation results from mcml is implemented in another program called "conv". Like the program mcml, it is written in ANSI Standard C, hence it can be executed on a variety of computers.

### **Convolution results of Gaussian beams**

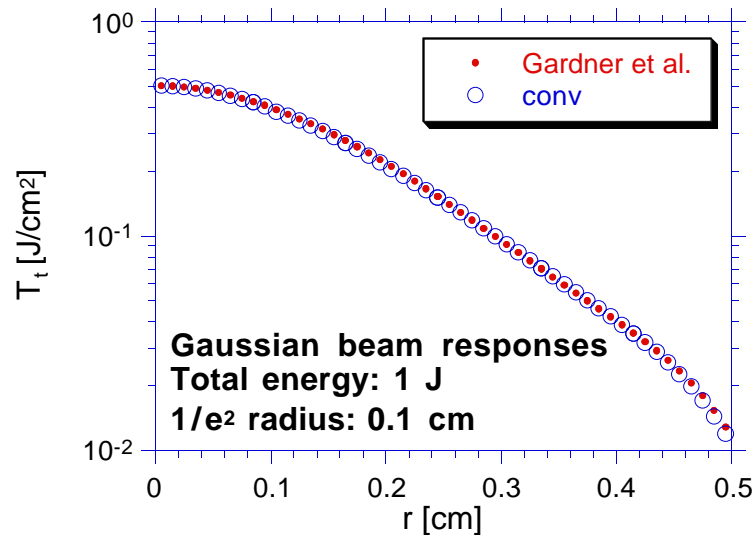
We do not have any standard data to verify the convolution program. However, Craig Gardner kindly provided some convolution results using his convolution program (Gardner *et al.*, 1992). The impulse responses are based on the simulation discussed in Section 6.6 where we have used the same turbid media and grid system. He computed his convolution on his Monte Carlo simulation results, and we did it on ours after we compared the Monte Carlo simulation results in Section 6.6.

The incident photon beam is a Gaussian beam with total energy of 1 J and radius of 0.1 cm. The convolved diffuse reflectances and transmittance are compared in Figs. 7.4 and 7.5 respectively. The convolved fluences are compared in Fig. 7.6. Note that the curves in Figs. 7.4-6 bend down faster near  $r$  equal 0.5 cm. This can be explained by the integrations in Eqs. 7.21. Due to the spatially limited range of the grid system (50 radial grids of 0.01 cm spacing, or  $r_{\max} = 0.5$  cm), the upper limit of the integration is cut by

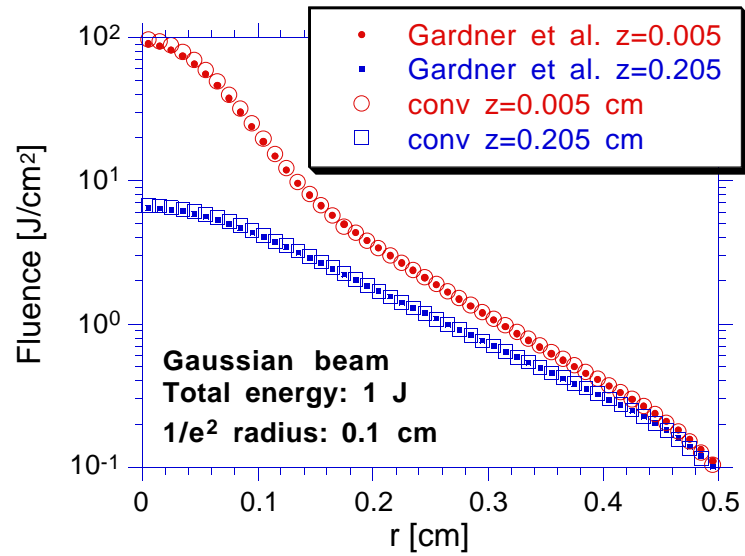
$r_{\max}$  more and more as the observation point  $r$  approaches  $r_{\max}$ . Therefore, the integration underestimates the true value.



**Fig. 7.4.** Comparison between diffuse reflectances as a function of  $r$  based on conv and Gardner's computation (Gardner *et al.*, 1992).

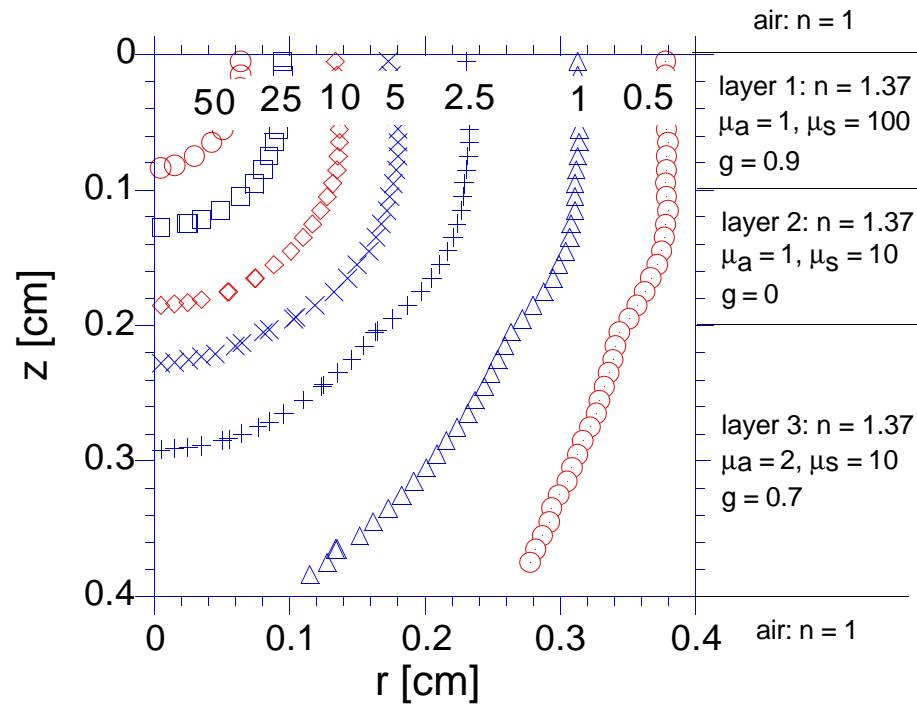


**Fig. 7.5.** Comparison between transmittances as a function of  $r$  based on conv and Gardner's computation (Gardner *et al.*, 1992).



**Fig. 7.6.** Comparison between fluences as a function of  $r$  for given  $z$  coordinates based on conv and Gardner's computation (Gardner *et al.*, 1992).

For 2D arrays such as the fluence as a function of  $r$  and  $z$ , conv has the ability to output the data in contour format (see Sections 10.9 and 10.10). The fluence as a function of  $r$  and  $z$  of the Gaussian beam is shown in contour lines in Fig. 7.7.

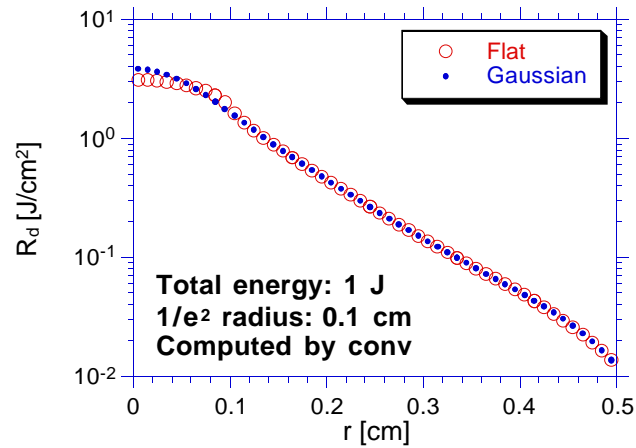


**Fig. 7.7.** Contour plot of the fluence [ $\text{J cm}^{-2}$ ] as a function of  $r$  and  $z$  based on conv for a Gaussian beam. The Gaussian beam has total energy of 1 J and  $1/e^2$  radius of 0.1 cm. The Monte Carlo simulation is for a three-layer tissue of Table 6.6. The absorption coefficient  $\mu_a$  and scattering coefficient  $\mu_s$  are in  $\text{cm}^{-1}$ .

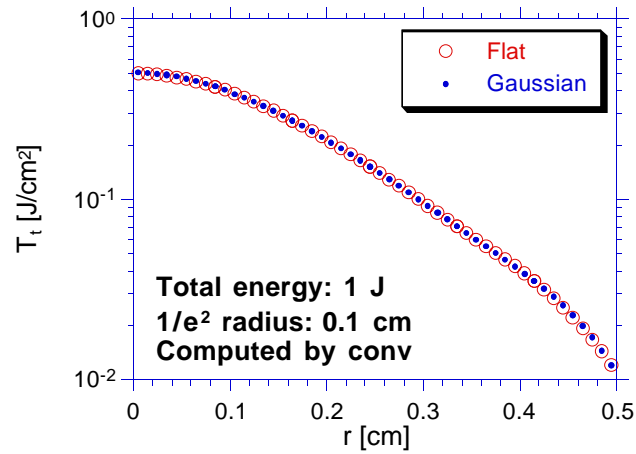
#### Convolution results of circularly flat beams

For circularly flat photon beams, we do not have other results for comparison. However, we would like to compare the results of circularly flat photon beams with that of Gaussian beams. The results of Gaussian beams are taken from the above computations. The circularly flat beam has 1 J of total energy and 0.1 cm of radius. The diffuse reflectances, transmittances and fluences are compared respectively in Figs. 7.8, 7.9, and 7.10.

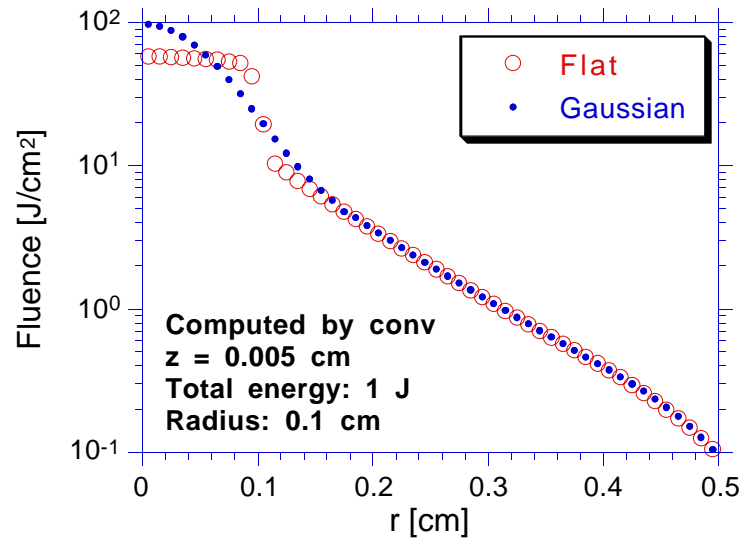




**Fig. 7.8.** Comparison between diffuse reflectances as a function of  $r$  convolved over a Gaussian beam and a flat beam using conv. Both beams have total energy of 1 J and radii of 0.1 cm.



**Fig. 7.9.** Comparison between transmittances as a function of  $r$  convolved over a Gaussian beam and a flat beam using conv. Both beams have total energy of 1 J and radii of 0.1 cm.

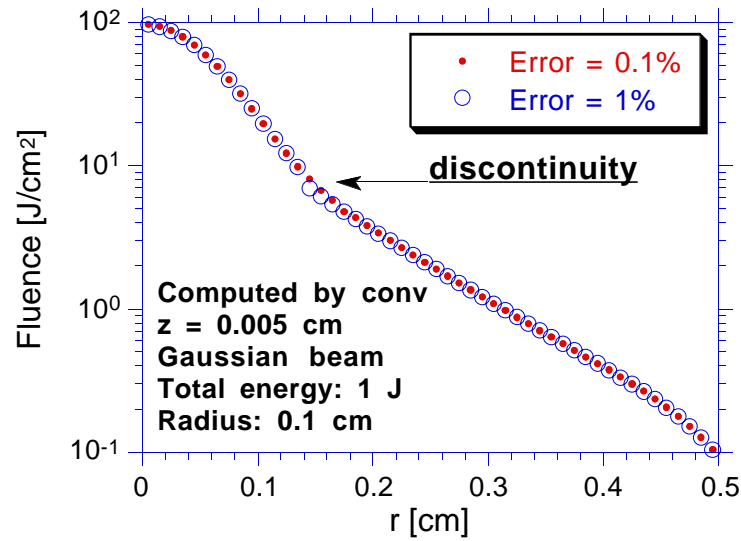


**Fig. 7.10.** Comparison between fluences as a function of  $r$  at  $z$  equal 0.005 cm convolved over a Gaussian beam and a flat beam using conv. Both beams have total energy of 1 J and radii of 0.1 cm.

It is observed that the Gaussian beam and the flat beam give nearly the same results when  $r$  is larger than about  $2R$ , where  $R$  is the radius of the beams. Furthermore, both kinds of responses bend down when  $r$  approaches 0.5 cm which is the grid limit in the  $r$  direction as discussed in last section.

### Convolution error

The convolution integration is computed iteratively. The iteration stops when the difference between the new estimate and the old estimate of the integration is a small part of the new estimate. This small ratio can be controlled by users using command "e". It ranges between 0 to 1. Small values would give better precision but longer computation time and vice versa. Normally, 0.001 to 0.1 is recommended. Sometimes, a high allowed error can cause some discontinuity in the convolved results. If this happens, choose a lower allowed convolution error and redo the convolution. For example, the convolution over a Gaussian beam in Fig. 7.10 has been done with an allowed convolution error of 0.001. If we choose the allowed convolution error to be 0.01, we can see the discontinuity in the fluence distribution (Fig. 7.11).



**Fig. 7.11.** Comparison between fluences as a function of  $r$  at  $z$  equal 0.005 cm convolved over a Gaussian beam with different allowed convolution errors using conv. The result with allowed error of 0.01 has discontinuity around  $r = 0.15$  cm. Using an allowed error of 0.001 eliminates the discontinuity. The Gaussian beams have total energy of 1 J and  $1/e^2$  radii of 0.1 cm.

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## **Part II. User Manual**

### **8. Installing mcml and conv**

This chapter provides the instructions on how to install the software. Since both mcml and conv are written in ANSI Standard C, they in principle should be able to be compiled on any computer systems that support ANSI C. Subject to the computer systems available to this laboratory, we will only provide the executables for Sun workstations, IBM PC compatibles, and Macintoshes. On Sun SPARCstations 2, we have compiled the mcml and conv using the ANSI C (acc). On IBM PC compatibles, we used Microsoft QuickC. And on Macintoshes, we used Symantec THINK C. We will provide the source code, users can feel free to compile them on their computer systems. Consult corresponding manuals for information on how to compile the code.

As Monte Carlo simulations are computationally intensive, we suggest that you use workstations such as Sun SPARCstations on which you can submit background jobs and which provide high speed computation. The convolution program is also more pleasant to use if you have a fast computer, although it is not as computation-intensive as Monte Carlo simulations.

#### **8.1 Installing on Sun workstations**

The distribution disk is an IBM format double density 3 1/2" disk, which Sun SPARCstation 2 should be able to read. All the files are packed into one file. Copy the file mcR1\_1.tar to a working directory using the command: `mcopy a:mcR1_1.tar .`, where the period means the current directory, and then untar the file using the command: `tar -xvfo mcR1_1.tar`.

The package includes three directories: mcmlcode, convcode, and Sun. The directory mcmlcode includes all the source code of mcml and the makefile used for acc. The directory convcode (not provided this time) includes all the source code of conv and the corresponding makefile. You need to modify the makefiles for other compilers (See Appendix C). The directory Sun includes all the executables, a template file of mcml input (template.mci), a sample mcml output file (sample.mco), and a short manual (mcmlconv.man) which is Chapter 8-10 of this manual.

To install the executables, copy the executables to the sub directory ~/bin under your home directory. Then, put the directory ~/bin under the search path in .cshrc or .login if you are using C Shell. Consult manual if you are using other shells.

Having finished copying, you can eject the disk using the command eject. If your Sun workstation does not have a floppy drive, you can transfer the files through a networked IBM PC or a compatible. If you have an electronic mail address, we can also send the package to you through mail.

## **8.2 Installing on IBM PC compatibles**

For IBM PC's or compatibles, the distribution disk is a double density 3 1/2" disk. An alternative 5 1/4" disk can be sent upon request. All the files are packed into one file. Copy the self-extracting file mcR1\_1.exe to your working directory on your hard drive and run the file to extract all packed files using the command: mcR1\_1.exe -d, where the option "-d" keeps the directory structure.

The package includes three directories: mcmlcode, convcode, and IBMPC. The directory mcmlcode includes all the source code of mcml. The directory convcode (not provided for now) includes all the source code of conv. The directory IBMPC includes all the executables, a template file of mcml input (template.mci), a sample mcml output file (sample.mco), and a short manual (mcmlconv.man) which is Chapter 8-10 of this manual. The executables include mcml.exe and conv.exe. The code was compiled and linked using Microsoft QuickC 2.5. The executables will be able to detect whether your computer has math coprocessor, and take advantage of the math coprocessors if they are present.

If you want to be able to execute the programs under any directory, you should put the directory IBMPC in the search path. The search path can be changed in the file autoexec.bat.

## **8.3 Installing on Macintoshes**

For Macintoshes, the distribution disk is a double density 3 1/2" disk. All the files are packed into one file. Copy the self-extracting file mcR1.1.sea to a working folder on you hard drive, and double click on the icon to extract the files.

The package includes three folders: mcmlcode, convcode, and Mac. The folder mcmlcode includes all the source code of mcml. The folder convcode includes all the

source code of conv. The folder Mac includes all the executables, a template file of mcml input (template.mci), a sample mcml output file (sample.mco), and a short manual (mcmlconv.man) which is Chapter 8-10 of this manual. The executables include mcml.fpu, conv.fpu, mcml.020, conv.020, mcml.000, and conv.000 for different types of computers as discussed subsequently.

Before you install the executables, you need to know what kind of Macintosh you are using. You can test the following conditions to decide which executables to use:

- A. MC68040
- B. MC68020 or MC68030
- C. MC68881 or MC68882

If your Macintosh meets condition A, or conditions B and C, you should copy the executables with extensions ".fpu". If your Macintosh meets condition B only, you should keep the executables with extensions ".020". Otherwise, you should use the executables with extensions ".000". We suggest that you remove the extensions of the executables on your hard drive to keep consistency with the manual.

#### **8.4 Installing by Electronic Mail**

For these users who have electronic mail access on UNIX machines, we can deliver the software package through electronic mails. The package is archived using the command tar, compressed using the command compress, then encoded using the command uuencode before it is mailed out using the mail utilities. After you receive the mail, you need to do the following.

1. Save the mail as a file, e.g., mc.mail.
2. Decode the file (mc.mail) to get a file named mc.tar.Z using  

```
uudecode mc.mail
```
3. Uncompress the file mc.tar.Z to get the file mc.tar  

```
uncompress mc.tar.Z
```
4. Unarchive the file mc.tar to get the package using:

---

```
tar -xvfo mc.tar
```

At this moment, you should have three directories under the working directory. They are mcmlcode, convcode, and Sun, or IBMPC, or Mac.

If you ordered a Sun version of the package, you only need to put the executables under the proper directory., e.g., ~/bin (see Section 8.1).

If you ordered an IBM PC version or a Mac version of the package, you need to transfer the files to your local computer using FTP or modem. Then refer to Section 8.2 or 8.3 for details.

It is appropriate to describe in more detail how we send the package through electronic mails which is exactly the opposite of the above procedure. We put the package in a working directory which include three subdirectories: mcmlcode, convcode, and Sun, or IBMPC, or Mac. Then:

```
tar -cvf mc.tar
compress mc.tar
uuencode mc.tar.Z mc.tar.Z > mc.mail
mail your_address
```

In the mail utility, you can add in any messages in the beginning of the mail, then you need to use the command `r` to read in the file `mc.mail`. Then, you can send the file by typing a period `.` and a return in a new line (see the manual page of mail).

## **9. Instructions for mcml**

This chapter describes the actual instructions to use mcml. Macintoshes, IBM PC compatibles and UNIX machines are used as examples of computer systems, although mcml can execute on any computer systems that support ANSI Standard C. The reader is assumed to be familiar with the operating system and comfortable with at least one of the text editors on the computer system to be used to execute mcml. Three steps involved in the Monte Carlo simulation using mcml are included in the following sections: preparing the input data file, executing the program mcml with the input data file, processing the output data in the data files named in the input data file. We will also show some known bugs.

### **9.1 File of input data**

The first step to do the simulation using mcml is to prepare an input data file (e.g., "filename.mci"). Any valid filenames on your system without spaces will be acceptable, but extension ".mci" is recommended. In ANSI C, spaces are used as separators. Therefore, filenames with spaces may not be accepted by mcml, although they are allowed by some operating systems themselves such as the Macintosh System. We will use "filename.mci" as an example in the following discussions.

This input data file may be edited with any text editors such as Apple Edit, MockWrite or Microsoft Word on Macintoshes, Norton editor NE or Microsoft Word on IBM PC compatibles, vi editor or EMACS on UNIX systems. However, if you use word processors like Microsoft Word to edit the file, make sure that you save the file in text format since mcml does not accept binary files as input. If you are using the UNIX system and are uncomfortable with vi or other editors available on UNIX, you can use editors on your personal computer, then transfer the file using Kermit if you use modem or FTP if your personal computer is on a network. Make sure to use ASCII or text mode when you transfer this file.

The best way to write an input data file is to make a copy of the template file called "template.mci" (See Appendix D), then modify the parameters in the file. The input data file is organized line by line. All parameters must be in the right order. The lines with parameters in order must also be in order themselves. However, feel free to insert comment lines or space lines in between to make the file more readable. Comment lines



---

start with the symbol "#". The symbol "#" can also be used after the parameters in a line to mark the start of comments.

The parameters in the input data file are read by mcml line by line. If there are multiple parameters in a line, use tabs or spaces to separate them. A tab is preferred, because it aligns the parameters for better readability. All dimensional quantities are in cm or derived from cm. The thickness of each layer is in cm. The grid line separations are also in cm. Absorption coefficient and scattering coefficient are in 1/cm. Each line of the input file is explained in the order that they appear in the input data file as follows.

1. File version of the input data file. Always use "1.0" for now.
2. Number of runs (integer). Each run is an independent simulation. You can specify any number of runs, which is not subject to memory limit. Make sure you use an integer instead of a floating point number for this parameter, e.g., 5 instead of 5.0.
3. Output filename and file format. Extension ".mco" is recommended for the output filenames, e.g., "output1.mco". The program mcml currently only supports ASCII format, therefore always use "A" as the second parameter in this line. Make sure that you use different output filenames if you have multiple runs in an input data file, although mcml checks for this mistake. What is more important is that the filenames should not be the same as the names of existent ones unless you want to overwrite the existent files on purpose. Since the program mcml does not check this error, you will lose the existent files.
4. Number of photon packets to be traced (integer).
5. Separations (in cm) between grid lines in z and r direction of the cylindrical coordinate system. These are floating point numbers. Both z and r originate from the photon incident point on the surface of first layer, and the z axis points down into the turbid medium. Make sure these parameters are large enough to give you an acceptable variance, and small enough to give you an acceptable resolution. These parameters should be determined coordinately with the number of photons to achieve both accuracy and resolution. Also note that users should try to choose grid size in the z direction so that grid boxes do not cross tissue-tissue interfaces or boundaries (see Section 9.5).

6. Number of grid elements (integers) in the z, r directions of the cylindrical coordinate system and in the alpha direction, where alpha is the angle spanned between the photon exiting direction and the surface normal. Since the angle always covers 0 through 90 degrees, the angular separation is 90 degrees divided by the number of angular grid elements specified in this line. Be careful with this line, if the numbers are too large, the output file will be very big because 2D arrays are written into the output file. If you do not need to resolve one of the directions (z or r) or the angle, use 1 (not 0) for that parameter. Make sure to use integers for these three parameters.
7. Number of layers (integer). This number does not include the ambient media above or below the tissue.
8. Refractive index for the top ambient medium above the first layer (e.g., 1.0 for air).
9. Layer parameter lines. One line for each layer. In each line are the refractive index, the absorption coefficient (1/cm), the scattering coefficient (1/cm), the anisotropy factor, and the thickness (cm). To simulate semi-infinite tissue, use a very large thickness (e.g., 1E8 cm) compared with the mean free path of the tissue.
10. Refractive index for the bottom ambient medium below the last layer (e.g., 1.0 for air).
11. Repeat lines 3 through 10 for each additional run if you have multiple runs.

Note: Two points are worth noting. The only limit to the number of grid elements and layers is the amount of memory allocated to mcml in your system because the arrays are dynamically allocated according to these parameters. Do not use floating point numbers for the integers. Otherwise, the program may interpret them incorrectly. However, you may use integers for floating point numbers, e.g., 100 instead of 100.0.

## **9.2 Execution**

Once the input data file is prepared, the program mcml can be executed using the input data file. During the execution, the program mcml will report an output message which gives the number of photons remaining in the simulation, the number of runs left, and the time of ending the job. The first report is after 10 photon packets are traced, then it

---

is updated when every 1/10 of the total number of photon packets are traced. The methods of execution are slightly different on different operating systems.

### Macintosh

To run mcml on Macintosh System 6, you have to copy or move the executable mcml to your working folder where the input data file resides, then double click on the mcml icon to start the program. The program mcml will prompt for the input data filename, which is entered through the keyboard. If the input data file cannot be found, the program will prompt you again until it finds the file or a period "." is typed, where "." is used to abort the program. If you use Macintosh System 7, you may use an alias of mcml instead of a copy of it.

### IBM PC compatibles

For IBM PC compatibles, make sure that the directory with mcml is in the search path, which can be checked by typing the command "path" or the file "autoexec.bat". To run mcml with the input data file as a command parameter under DOS command prompt, type:

```
mcml filename.mci
```

If you want to save the output message as a file (e.g., message.out), type:

```
mcml filename.mci > message.out
```

which redirects the output message to the file "message.out". To run mcml in the interactive mode, type the following command without input data filename:

```
mcml
```

Then, the program mcml will prompt for the input data file.

### UNIX

On a UNIX system, you should place the executable mcml in a directory that is in the search path. The directory ~/bin is a good choice. The search path can be found and modified in the file ".cshrc" if you are using C Shell or the file ".login". The three ways of

invoking mcml under DOS can be used under UNIX operating systems. Moreover, if you wish to discard the messages during the execution, use the command:

```
mcml filename.mci > /dev/null
```

which redirects the output to the "bit bucket" (/dev/null). You can also simply submit a background job using:

```
mcml filename.mci > /dev/null &
```

Refer to your UNIX manual for how to inquire about the status of a background job. If you are still in the same session, the command "jobs" can be used in C Shell. Otherwise, you should use the UNIX command "ps" to check for background processes. You can also directly look for the output files to check if the job is done.

### **9.3 File of output data**

When the job is completed, the results will be written into the output data files as you named in your input data file. A sample output data file is shown in Appendix E. The output data files can be read with any text editors if they are ASCII as a result of using "A" for the file format in the input data file. They may be big if your numbers of grid elements are large.

The contents of output files are self explanatory. The same policy for the input data file is used for the output data file, that is, comment lines starting with a symbol "#" and space lines are written to the file for clarity. The first line is used for file type identification when the file is read by other applications. Then, the user time spent on the simulation is reported in a comment line. Then, a few categories of data are reported sequentially in the following order: pure numbers, 1D arrays and 2D arrays. The definitions of the output data can be found in Chapter 4. The category "InParm" reports all the input parameters specified in the input data file again so that the output file is a complete reference and the input parameters may also be double checked against any errors in the input data file. The category "RAT" reports the specular reflectance, the total diffuse reflectance, the total absorption, and the total transmittance. The category "A\_l" is the absorption as a function of layer. The category "A\_z" is the absorption as a function of depth z. The categories "Rd\_r" and "Rd\_a" are the diffuse reflectances as a function of radius r and angle alpha respectively. The categories "Tt\_r" and "Tt\_a" are the transmittance as a function of radius r and angle alpha respectively. The 2D arrays A\_rz, Rd\_ra, and Tt\_ra are then reported.

The category  $A_{rz}$  is the absorption as a function of depth  $z$  and radius  $r$ . The categories  $Rd_{ra}$  and  $Tt_{ra}$  are correspondingly the diffuse reflectance and transmittance as a function of radius  $r$  and angle  $\alpha$ . The name of each category is written before the data, such that the data can be easily identified. The units for these data were discussed in Chapter 4.

#### **9.4 Subset of output data**

Sometimes, only a subset of the output data is needed for presentation or processing. For example, we may need to print a 1D array into a file in XY format, namely two columns of data, or a 2D array in XYZ format. These files can then be read into some commercial applications such as AXUM on IBM PC compatibles and KaleidaGraph on Macintoshes. This subset extraction can be done using another program -- conv. The program conv is intended to read in the output data file of mcml that gives responses of infinitely narrow photon beam, and convolve the output data if the responses of finite size beam are to be computed. The program conv can output the original data or the convolved data in various formats. The convolution part of the program conv has not been finished, although it can be used to extract subsets of the original output data.

The program conv is made to be interactive. After the program is invoked, the menu system will direct the data input, output, or process. On Macintosh, copy or move the program conv to your working folder. Start conv by double clicking on the icon. On IBM PC compatibles or UNIX machines, invoke the program conv by typing:

```
conv
```

Follow the menu to input an mcml output file (e.g., "filename.mco"). Then, output specific data to new files. However, for the sake of efficiency, we wrote a C Shell script file "conv.bat" for UNIX users. For shell programming, refer to Anderson *et al.* (1986) or Arthur (1990). A similar file can be written on MS-DOS operating system. The file "conv.bat" is used for fast batch process. For example, if there are several mcml output files named "outfile1.mco", "outfile2.mco"... "outfilen.mco", and you need to select the diffuse reflectance as a function of radius  $r$  of these mcml output files on a UNIX system, then you can use the command:

```
conv.bat "outfile*.mco" Rr
```

This command takes two arguments. The first one gives the mcml output files to be processed. If wild cards, such as \* or ?, are used, the argument has to be within quotes to

prevent immediate file expansion. The second argument gives the type of subsets to be extracted. In this case, it is the diffuse reflectance as a function of  $r$ . The files of the subsets will be named as "outfile\*.Rr". In each of these output files, there are two columns, the first one is the radius, and the second one is the reflectance. To check the complete usage of "conv.bat", type "conv.bat" on command line. More examples are:

```
conv.bat "outfile*.mco" Az
```

for 1D absorption as a function of  $z$ . In each of the output files of this command, there are two columns representing  $z$  and the internal absorption respectively.

```
conv.bat "outfile*.mco" Azr
```

for 2D absorption as a function of  $z$  and  $r$ . In each of the output files of this command, there are three columns representing  $z$ ,  $r$ , and the internal absorption respectively.

If you use UNIX to do the simulation and want to present the results using Macintosh or IBM PC compatibles, transfer the smaller subset files using KERMIT if you use modem or FTP if you use Ethernet.

### **9.5 Bugs of mcml**

1. Users have to be careful with several known bugs about the program mcml version 1.0. If a grid element crosses a medium interface, e.g., a glass/tissue interface, the photon absorption within this grid element is considered to be the absorption in the medium where the center of the grid element is located. Therefore, if the center is on the side of the glass, mcml may report small absorption in the glass. Sometimes, this problem may be avoided by choosing the  $z$ -grid system carefully so that the boundaries of elements align with the layer interfaces.
2. The user time of a simulation can be reported as zero if the simulation is long enough to overflow the timer (See the function `clock()` in the file "mcmlmain.c").
3. The input parameters in the input data file have to be in the order as specified. Furthermore, you have to use integers for number of photon packets, number of layers, and number of grid elements in the input data file. If floating point numbers are inadvertently used, mcml can not detect the error and may read in the wrong parameters.

If you find any new bugs, please report to us using the information in Appendix G. It is very important that you provide us enough information about the bug so that we can reproduce it.

## 10. Instructions for conv

This chapter describes the instructions to use the program conv, which is used to convolve the impulse responses of mcml over incident beams of finite size. This program reads the output of mcml, then convolves the impulse responses according to the user specified incident beams. The program can output the original data from mcml or the convolved data in various ASCII formats as discussed subsequently.

### 10.1 Start conv

To start conv on IBM PC compatibles or UNIX machines, invoke the program conv by typing:

```
conv
```

To use conv on Macintoshes, copy or move the program conv to your working folder. Then, double click the conv icon to start it. If you are using System 7, you may take advantage of the alias mechanism.

### 10.2 Main menu of conv

Once conv is started, it is in the main menu of the program after showing some information about the program. In the main menu, the program prompts for a command as:

```
> Main menu (h for help) =>
```

To show all the available command, type "h" and return key. It will show you the following information and prompt for the next command. You only need to show the help information when you forget the commands.

```
i = Input filename of mcml output  
b = specify laser Beam  
r = convolution Resolution.  
e = convolution Error.  
oo = Output Original data  
oc = Output Convolved data  
co = Contour output of Original data  
cc = Contour output of Convolved data  
so = Scanning output of Original data  
sc = Scanning output of Convolved data  
q = Quit  
* Commands in conv are not case-sensitive
```

```
> Main menu (h for help) =>
```



Each command will be introduced subsequently.

### **10.3 Command "i" of conv**

You have to provide the filename of the mcml output to conv. This can be done by typing "i" and return key in the main menu prompt, then type in the filename of the mcml output. For example:

```
> Main menu (h for help) => i
Input filename of mcml output(or . to quit): example.mco
> Main menu (h for help) =>
```

The program returns to the main menu automatically. If the file cannot be located or opened, the program will prompt you to type in another filename. You can also type "." and return key to quit inputting the filename. If the file is not the output of mcml, the program will quit to the operating system. You need to start the program again.

### **10.4 Command "b" of conv**

You need to specify the type and parameters of the incident beam. In version 1.0 of conv, only Gaussian beams and circularly flat (rectangular) beams are supported. To enter the incident beam, use command "b". Then you have to choose from "f" for flat beam, "g" for Gaussian beam, or "q" to quit this command. If you choose either flat beam or Gaussian beam., conv asks the total energy and the radius of the beam. For example:

```
> Main menu (h for help) => b
Beam profile:f=flat, g=Gaussian. q=quit: f
Total energy of the flat beam [J]: 1
Radius of the flat beam [cm]: .1
Total power:          1 J, and radius:          0.1 cm.
> Main menu (h for help) =>
```

It returns to the main menu automatically. Although we specify units of energy for the incident beam, you can substitute units of power throughout the program. To get reliable results, the radius should be much larger than the grid separation in the r direction of the original mcml output, and much less than the total covered radius by the grid system in the r direction of the original mcml output. As a rule of thumb, the radius should be in the range between about 3 times the grid separation in the r direction and the total grid coverage in the r direction minus the maximum radius of observation (see Eqs. 7.23 & 7.24 in Section 7.4).

### **10.5 Command "r" of conv**

This command is used to change the grid separation and the number of grid elements in the r direction for the convolution. Since they take the values of the mcml output as the default, you do not have to enter this command if you do not want to change them. The maximum convolution radius should not be larger than that of the original mcml output to get reliable results. For example:

```
> Main menu (h for help) => r
Current resolution:      0.01 cm and number of points: 50
Input resolution in r direction [cm]: .02
Input number of points in r direction: 20
Resolution:      0.02 cm and number of points: 20

> Main menu (h for help) =>
```

Note that if the number of points is chosen too large, the program can exit due to the lack of memory. This is a bug in the current version of conv.

### **10.6 Command "e" of conv**

The integration is computed iteratively. The iteration stops when the difference between the new estimate and the old estimate of the integration is a small part of the new estimate. This small ratio can be controlled by users using command "e". It ranges between 0 to 1. Small values would give better precision but longer computation time and vice versa. Normally, 0.001 to 0.1 is recommended. The default value is 0.1. For example:

```
> Main menu (h for help) => e
Relative convolution error
Current value is 0.05 (0.001-0.1 recommended): .01
```

Special attention has to be paid to this command. The convolution results may have weird discontinuities if the allowed convolution error is too high (see Fig. 7.11), and the convolution process may take too long if the convolution error is too low. The rule of thumb is that you choose the lowest convolution error that does not make the convolution too long to compute. If the convolution results still have any discontinuities which should not be there, you need to decrease the convolution error and redo the convolution.

### 10.7 Command "oo" of conv

After you input the filename of the mcml output, you can output the original data of the mcml output with various formats. One of the formats can be obtained by the command "oo". For example:

```
> Main menu (h for help) => oo

> Output mcml data (h for help) => h
I   = Input parameters of mcml
3   = reflectance, absorption, and transmittance
AL  = absorption vs layer [-]
Az  = absorption vs z [1/cm]
Arz = absorption vs r & z [1/cm3]
Fz  = fluence vs z [-]
Frz = fluence vs r & z [1/cm2]
Rr  = diffuse reflectance vs radius r [1/cm2]
Ra  = diffuse reflectance vs angle alpha [1/sr]
Rra = diffuse reflectance vs radius and angle [1/(cm2 sr)]
Tr  = transmittance vs radius r [1/cm2]
Ta  = transmittance vs angle alpha [1/sr]
Tra = transmittance vs radius and angle [1/(cm2 sr)]
K   = Keijzer's format
Q   = Quit to main menu
* input filename: example.mco

> Output mcml data (h for help) =>
```

At this point, you can output various physical quantities by inputting the subcommands, which can be listed by command "h" as shown above. After you type the command, the program will ask you for the output filename. The exact physical meanings of these physical quantities can be found in Chapter 4. The command "i" outputs the input parameters of mcml to a file. The command "3" outputs three quantities to a file including specular reflectance, total diffuse reflectance, absorption probability, and total transmittance, which are actually four numbers. The command "Al" outputs the absorption probability as a function layer to a file. The command "Az" outputs the absorption as a function of z coordinate whose dimension is  $\text{cm}^{-1}$ . The command "Arz" outputs the absorption probability density as a function of r and z whose dimension is  $\text{cm}^{-3}$ . The commands "Fz" and "Frz" output the results of the commands "Az" and "Arz" divided by the absorption coefficients. The command "Rr" outputs the diffuse reflectance as a function of r whose unit is  $\text{cm}^{-2}$ . The command "Ra" outputs the diffuse reflectance as a function of the exit angle  $\alpha$ , whose dimension is  $\text{sr}^{-1}$ . The command "Rra" outputs the diffuse reflectance as a function of r and  $\alpha$ , whose unit is  $\text{cm}^{-2} \text{sr}^{-1}$ . Similarly, the commands "Tr", "Ta" and "Tra" are the corresponding commands for the transmittance. The command "K" is used to convert the format of the mcml output to the format of

Marleen Keijzer's convolution program (in PASCAL on Macintoshes) which was used by our group before the program conv was written. This command is only useful if you have Marleen Keijzer's program. The command "q" will return the program to the main menu.

For 1D arrays, the outputs are in two columns. The first column gives the independent variable, and the second column gives the physical quantities. For example, the output of the command "Rr" will have two columns. The first column gives the radius in cm, and the second column gives the diffuse reflectance in  $\text{cm}^{-2}$ .

For 2D arrays, the outputs are in three columns. The first two columns give the first and the second independent variables, and the third column gives the physical quantities. For example, the command "Arz" will give three columns. The first two columns give r and z in cm respectively, and the third column gives the absorption probability density in  $\text{cm}^{-2} \text{sr}^{-1}$  as a function of r and z.

An example is shown as follows:

```
> Output mcml data (h for help) => Rr
Enter output filename with extension .Rr (or . to quit): example.Rr

> Output mcml data (h for help) =>
```

This command will output the diffuse reflectance as a function of r to the file named "example.Rr".

### **10.8 Command "oc" of conv**

After you input the filename of the mcml output and specify the incident photon beam, you can output the convolved data with various formats. One of the formats is writing data in columns, which can be obtained using the command "oc". For example:

```
> Main menu (h for help) => oc

> Output convolved data (h for help) => h
Arz = absorption vs r & z [J/cm3]
Frz = fluence vs r & z [J/cm2]
Rr  = diffuse reflectance vs radius r [J/cm2]
Rra = diffuse reflectance vs radius and angle [J/(cm2 sr)]
Tr  = transmittance vs radius r [J/cm2]
Tra = transmittance vs radius and angle [J/(cm2 sr)]
Q   = Quit to main menu
* input filename: example.mco

> Output convolved data (h for help) =>
```

At this point, you can output various physical quantities by inputting the subcommands, which can be listed by command "h" as shown above. After you type the command, the program will ask you for the output filename. The exact physical meanings of these physical quantities can be found in Chapters 4 and 7. The command "Arz" outputs the absorption energy density as a function of r and z whose dimension is  $\text{J cm}^{-3}$ . The command "Frz" outputs the results of the command "Arz" divided by the absorption coefficients, which is the fluence in  $\text{J cm}^{-2}$ . Since we consider steady-state responses only in mcml and conv, you can systematically replace the energy [Joules] with power [Watts] in conv.

The command "Rr" outputs the diffuse reflectance as a function of r whose unit is  $\text{J cm}^{-2}$ . The command "Rra" outputs the diffuse reflectance as a function of r and  $\alpha$ , whose unit is  $\text{J cm}^{-2} \text{ sr}^{-1}$ . Similarly, the commands "Tr" and "Tra" are the corresponding commands for the transmittance. The command "q" will return the program to the main menu.

For 1D arrays, the outputs are in two columns. The first column gives the independent variable, and the second column gives the physical quantities. For example, the output of the command "Rr" will have two columns. The first column gives the radius in cm, and the second column gives the diffuse reflectance in  $\text{J cm}^{-2}$ .

For 2D arrays, the outputs are in three columns. The first two columns give the first and the second independent variables respectively, and the third column gives the physical quantities. For example, the command "Arz" will give three columns. The first two columns give r and z in cm respectively, and the third column gives the absorption energy density in  $\text{J cm}^{-2} \text{ sr}^{-1}$  as a function of r and z.

An example is shown as follows:

```
> Output convolved data (h for help) => Rr
Enter output filename with extension .Rrc (or . to quit): example.Rrc
> Output convolved data (h for help) =>
```

This command will output the diffuse reflectance as a function of r to the file named "example.Rrc".

### 10.9 Command "co" of conv

After you input the filename of the mcml output, you can output the original data of the mcml output with various formats. One of the formats for 2D arrays is writing data in contour lines. Every contour line will be given by two columns. This format can be obtained using the command "co" standing for "contours of the original data". Then, the output file can be imported to some plotting software such as KaleidaGraph on Macintoshes, and the contour lines can be drawn. For example:

```
> Main menu (h for help) => co

> Contour output of mcml data (h for help) => h
A = absorption vs r & z [1/cm3]
F = fluence vs r & z [1/cm2]
R = diffuse reflectance vs radius and angle [1/(cm2 sr)]
T = transmittance vs radius and angle [1/(cm2 sr)]
Q = Quit to main menu
* input filename: example.mco

> Contour output of mcml data (h for help) =>
```

Since only the 2D arrays need to be presented in contour lines, there are only four physical quantities. The command "A" outputs the absorption probability density as a function of r and z whose dimension is  $\text{cm}^{-3}$ . The command "F" outputs the probability fluence as a function of r and z in  $\text{cm}^{-2}$ . The commands "R" and "T" output diffuse reflectance and transmittance as a function of r and  $\alpha$  in  $\text{cm}^{-2} \text{sr}^{-1}$ .

After you input one of the commands, the program will prompt for the output filename and the isovalues for the contour output. The value range of the physical quantity is shown so that valid isovalues can be provided by users. You can enter as many isovalues as you want. System memory is the only thing that limits the number of isovalues. Stop entering isovalues by inputting a period ".". For example:

```
> Contour output of mcml data (h for help) => A
Enter output filename with extension .iso (or . to quit): example.iso
The range of the value is 0.156280 to 3294.800000.
Input an isovalue or . to stop: 1000
Input an isovalue or . to stop: 100
Input an isovalue or . to stop: 10
Input an isovalue or . to stop: 1
Input an isovalue or . to stop: .

> Contour output of mcml data (h for help) =>
```

The output file of this example will have eight columns, each pair of columns describe one contour line. The values of the contour lines are 1000, 100, 10, and 1 respectively.

### 10.10 Command "cc" of conv

After you input the filename of the mcml output and specify the incident photon beam, you can output the convolved data with various formats. One of the formats for 2D arrays is writing data in contour lines. Every contour line will be given by two columns. This format can be obtained using the command "cc". The output file can be imported to some plotting software such as KaleidaGraph, and the contour lines can be drawn. For example:

```
> Main menu (h for help) => cc

> Contour output of convolved data (h for help) => h
A = absorption vs r & z [J/cm3]
F = fluence vs r & z [J/cm2]
R = diffuse reflectance vs radius and angle [J/(cm2 sr)]
T = transmittance vs radius and angle [J/(cm2 sr)]
Q   = Quit to main menu
* input filename: example.mco

> Contour output of convolved data (h for help) =>
```

Since only the 2D arrays need to be presented in contour lines, there are only four physical quantities. The command "A" outputs the absorption energy density as a function of r and z whose dimension is  $\text{J cm}^{-3}$ . The command "F" outputs the fluence as a function of r and z in  $\text{J cm}^{-2}$ . The commands "R" and "T" output diffuse reflectance and transmittance as a function of r and  $\alpha$  in  $\text{J cm}^{-2} \text{sr}^{-1}$  respectively.

After you input one of the commands, the program will prompt for the output filename and the isovalues for the contour output. The value range of the physical quantity is shown so that valid isovalues can be provided by users. You can enter as many isovalues as you want. System memory is the only thing that limits the number of isovalues. Stop entering isovalues by inputting a period ".". For example:

```
> Contour output of convolved data (h for help) => A
Enter output filename with extension .iso (or . to quit): exampleAc.iso
The range of the value is 0.048200 to 95.624939.
Input an isovalue or . to stop: 80
Input an isovalue or . to stop: 8
Input an isovalue or . to stop: 0.8
Input an isovalue or . to stop: .

> Contour output of convolved data (h for help) =>
```

The output file of this example will have six columns, each pair of columns describe one contour line. The values of the contour lines are 80, 8, and 0.8 respectively.

### 10.11 Command "so" of conv

After you input the filename of the mcml output, you can output the original data of the mcml output with various formats. One of the formats for 2D arrays is writing data in two columns, where the two columns give the physical quantity as a function of one of two independent variables. The other variable is fixed at a certain value which can be chosen by users. This format, we call scanning output, can be obtained using the command "so". The output file can be imported to some plotting software such as KaleidaGraph. For example:

```
> Main menu (h for help) => so

> Scans of mcml data (h for help) => h
Ar = absorption vs r @ fixed z [1/cm3]
Az = absorption vs z @ fixed r [1/cm3]
Fr = fluence vs r @ fixed z [1/cm2]
Fz = fluence vs z @ fixed r [1/cm2]
Rr = diffuse reflectance vs r @ fixed angle [1/(cm2 sr)]
Ra = diffuse reflectance vs angle @ fixed r [1/(cm2 sr)]
Tr = transmittance vs r @ fixed angle [1/(cm2 sr)]
Ta = transmittance vs angle @ fixed r [1/(cm2 sr)]
Q = quit
* input filename: example.mco

> Scans of mcml data (h for help) =>
```

The command "Ar" outputs the absorption probability density as a function of  $r$  for a fixed  $z$ , whose dimension is  $\text{cm}^{-3}$ . The command "Az" outputs the absorption probability density as a function of  $z$  for a fixed  $r$ , whose dimension is  $\text{cm}^{-3}$ . The command "Fr" outputs the probability fluence as a function of  $r$  for a fixed  $z$  in  $\text{cm}^{-2}$ . The command "Fz" outputs the probability fluence as a function of  $z$  for a fixed  $r$  in  $\text{cm}^{-2}$ . The command "Rr" outputs the diffuse reflectance as a function of  $r$  for a fixed  $\alpha$  in  $\text{cm}^{-2}\text{sr}^{-1}$ . The command "Ra" outputs the diffuse reflectance as a function of  $\alpha$  for a fixed  $r$  in  $\text{cm}^{-2}\text{sr}^{-1}$ . The commands "Tr" and "Ta" output the transmittance in the same format as for the diffuse reflectance. The command "q" returns to the main menu.

After you input one of the commands, the program will prompt for the output filename and the grid index to the value of the fixed variable. If you want to abort this output, you can input a period "." as the filename. For example:

```
> Scans of mcml data (h for help) => Ar
Enter output filename with extension .Ars (or . to quit): example.Ars
z grid separation is 0.01      cm.
Input fixed z index (0 - 39): 0

> Scans of mcml data (h for help) =>
```



This command outputs the absorption as a function of  $r$  for a fixed  $z$ . The program shows that the  $z$  grid separation is 0.01 cm. The number of grid elements in the  $z$  direction is 40. The grid index in the  $z$  direction is in the range from 0 to 39. The command will generate two columns. The first column is  $r$ , and the second is the absorption.

### **10.12 Command "sc" of conv**

After you input the filename of the mcml output and specify the incident photon beam, you can output the convolved data with various formats. One of the formats for 2D arrays is writing data in two columns, where the two columns give the physical quantity as a function of one of two independent variables. The other variable is fixed at a certain value which can be chosen by users. This format, we call scanning output, can be obtained using the command "sc". Then, the output file can be imported to some plotting software such as KaleidaGraph. For example:

```
> Main menu (h for help) => sc

> Scans of convolved data (h for help) => h
Ar = absorption vs r @ fixed z [J/cm3]
Az = absorption vs z @ fixed r [J/cm3]
Fr = fluence vs r @ fixed z [J/cm2]
Fz = fluence vs z @ fixed r [J/cm2]
Rr = diffuse reflectance vs r @ fixed angle [J/(cm2 sr)]
Ra = diffuse reflectance vs angle @ fixed r [J/(cm2 sr)]
Tr = transmittance vs r @ fixed angle [J/(cm2 sr)]
Ta = transmittance vs angle @ fixed r [J/(cm2 sr)]
Q = quit
* input filename: example.mco

> Scans of convolved data (h for help) =>
```

The command "Ar" outputs the absorption energy density as a function of  $r$  for a fixed  $z$ , whose dimension is  $\text{J cm}^{-3}$ . The command "Az" outputs the absorption energy density as a function of  $z$  for a fixed  $r$ , whose dimension is  $\text{J cm}^{-3}$ . The command "Fr" outputs the fluence as a function of  $r$  for a fixed  $z$  in  $\text{J cm}^{-2}$ . The command "Fz" outputs the fluence as a function of  $z$  for a fixed  $r$  in  $\text{J cm}^{-2}$ . The command "Rr" outputs the diffuse reflectance as a function of  $r$  for a fixed  $\alpha$  in  $\text{J cm}^{-2} \text{sr}^{-1}$ . The command "Ra" outputs the diffuse reflectance as a function of  $\alpha$  for a fixed  $r$  in  $\text{J cm}^{-2} \text{sr}^{-1}$ . The commands "Tr" and "Ta" output the transmittance in the same format as for the diffuse reflectance. The command "q" returns to the main menu.

After you input one of the commands, the program will prompt for the output filename and the grid index to the value of the fixed variable. If you want to abort this output, you can input a period "." as the filename. For example:

```
> Scans of convolved data (h for help) => Ar
Enter output filename with extension .Arsc (or . to quit): example.Arcs
z grid separation is 0.01      cm.
Input fixed z index (0 - 39): 0

> Scans of convolved data (h for help) =>
```

This command outputs the absorption as a function of  $r$  for a fixed  $z$ . The program shows that the  $z$  grid separation is 0.01 cm. The number of grids in the  $z$  direction is 40. The grid index in the  $z$  direction is in the range from 0 to 39. The command will generate two columns. The first column is  $r$ , and the second is the absorption.

### **10.13 Command "q" of conv**

If you want to quit the program conv, use the command "q" in the main menu. The program will ask you if you really mean to quit. You can answer yes or no. The program will quit if the answer is "y". Otherwise, the program will return to the main menu. For example:

```
> Main menu (h for help) => q
Do you really want to quit conv (y/n): n

> Main menu (h for help) => q
Do you really want to quit conv (y/n): y
```

### **10.14 Bugs of conv**

The convolution results may have weird discontinuities if the allowed convolution error is too high, and the convolution process may take too long if the convolution error is too low. We do not have a good way to predict the best convolution error yet. The rule of thumb is that you choose the lowest convolution error that does not make the convolution too long to compute. If the convolution results still have any discontinuities which should not be there, you need to decrease the convolution error and redo the convolution.

As we discussed in Section 7.5, the radius of the incident beam has to be in the right range to get reliable convolution integration due to the spatial resolution and the range of grid system. As a rule of thumb, the radius should be in the range between about 3

times the grid separation in the  $r$  direction and the total grid coverage in the  $r$  direction minus the maximum radius of observation (see Eqs. 7.23 & 7.24 in Section 7.4).

If the number of points in the  $r$  direction is chosen too large in the command "r", the program can exit due to the lack of memory.

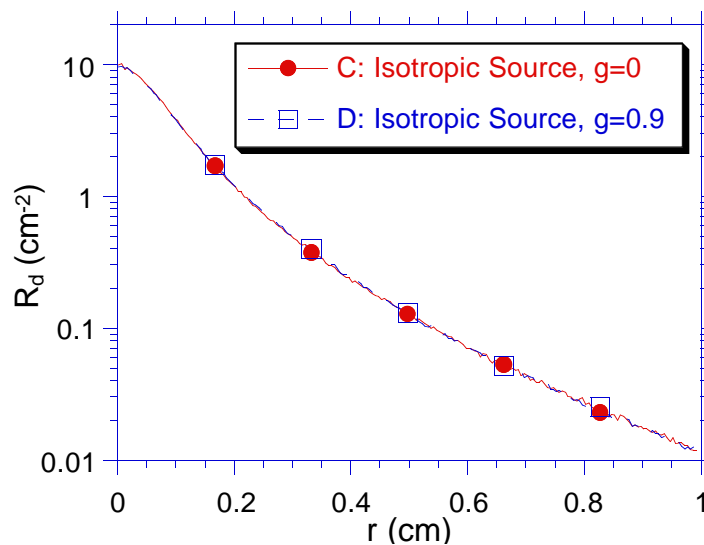
## 11. How to Modify mcml

The current version of program mcml simulates responses of an infinitely narrow photon beam normally incident on multi-layered turbid media. We intend to make mcml more general in the future. However, if you need to solve a different problem, such as responses of isotropic photon sources instead of infinitely narrow photon beams, responses of buried beams instead of externally incident beams, or time-resolved simulations, then you will need to modify the program slightly. To do so, you need to have prior knowledge of C language and understand Chapter 5. Appendix A and Appendix B are provided to aid you in modifying the program. Appendix A gives you an overall flow of the program, and Appendix B provides line-numbered source codes, which can be used in combination with Appendix A for quick reference of the detail of the program.

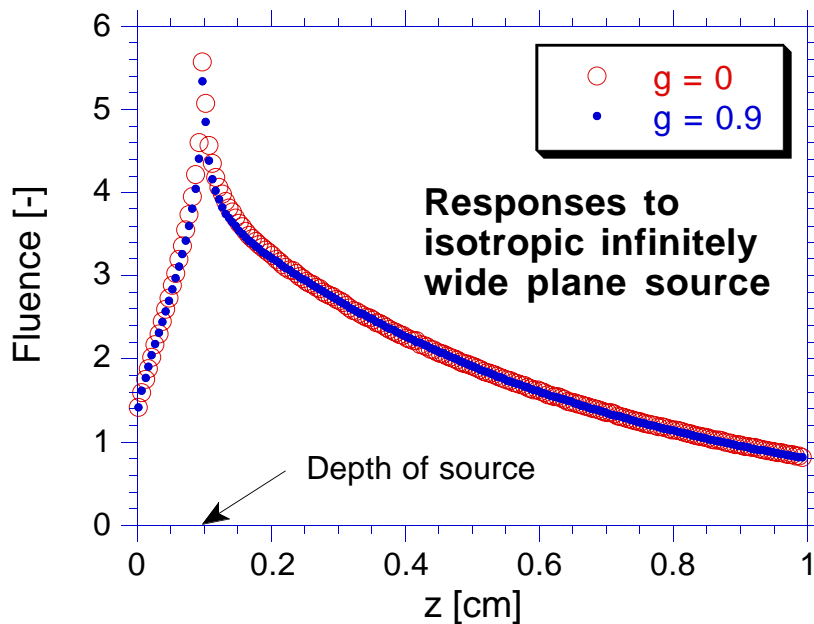
As an example, let us modify several places of the program mcml to compute the responses of buried isotropic photon sources. First, we need to allow users to provide the depth of the isotropic photon source inside the tissue, which can be entered in the input data file. For example, we can add the depth of the source as the second parameter in the line for the number of photon packets. Second, we define one more member called `source_z` in the structure `InputStruct` to store the depth of the source. Third, we read the depth into the member `source_z` of structure `InputStruct` in function `ReadParm()` which is in the file "mcmlio.c". Fourth, we need to modify the function `LaunchPhoton()` in the file "mcmlgo.c" such that the photons are initialized isotropically at the correct depth according to `source_z`. If you know the program well, you will know that you can make the source isotropic utilizing the function `Spin()` in the file "mcmlgo.c". To do so, we can initialize the photon packet to be unidirectional (e.g., +z direction) temporarily, then pretend that the whole photon packet suffers an isotropic scattering on the same spot as initialized using the function `Spin()`. All you need to do is to provide an anisotropy factor  $g$  equal 0 as the real parameter for the function. The propagation simulation functions need no change, and the scoring procedures need no change either because the problem is still cylindrically symmetric. After you modify the source code, you need to recompile and link (refer to the manual with the compiler and linker).

After we modified mcml like this, we simulated the diffuse reflectances of a buried isotropic photon source in two media separately, whose optical properties are equivalent according to the similarity relations (Wyman *et al.*, 1989a and 1989b). The optical properties for the isotropic scattering medium ( $g = 0$ ) are: absorption coefficient  $\mu_a = 0.1$

$\text{cm}^{-1}$ , scattering coefficient  $\mu_s = 10 \text{ cm}^{-1}$ , anisotropy factor  $g = 0$ , relative refractive index  $n_{\text{rel}} = 1$ . The optical properties for the anisotropic scattering medium ( $g \neq 0$ ) are:  $\mu_a = 0.1 \text{ cm}^{-1}$ ,  $\mu_s = 100 \text{ cm}^{-1}$ ,  $g = 0.9$ ,  $n_{\text{rel}} = 1$ . The depth of the isotropic photon source is 1 transport mean free path (mfp'), which is computed by  $1 \text{ mfp}' = 1/(\mu_a + \mu_s(1-g)) = 1/(0.1 + 10) \approx 0.1 \text{ cm}$ . The grid separations in the  $z$  and  $r$  directions are both  $0.005 \text{ cm}$ , and the numbers of grid elements in the  $z$  and  $r$  directions are both 200. One million photon packets were used in the modified mcml.



**Fig. 11.1.** Comparison of diffuse reflectances as a function of radius  $r$  for two semi-infinite media whose optical properties are governed by the similarity relations. The diffuse reflectances and the fluences for the two media are compared in Figs. 11.1 and 11.2 respectively. The results of the diffuse reflectances show that the similarity relations work well for photon sources deep inside the tissue, and the results of the fluences show that the similarity relations work well when the observation point is far away from the source. The fluence near the source for the isotropic scattering medium is larger than that for the anisotropic scattering medium. Similar to the discussion in Section 4.2, the fluences presented here are the responses of an isotropic infinitely wide plane source with a difference of a constant factor which is the power density of the source.



**Fig. 11.2.** Comparison between fluences as a function of  $z$  for two semi-infinite media whose optical properties are governed by the similarity relations (see Section 4.2 for discussion of an infinitely wide incident beam).

## Appendices

### Appendix A. Cflow Output of the Program mcml

We have listed the short format of the UNIX command cflow output in Section 5.5. To show all depth of the nesting levels, we list here the results of the UNIX command:

```

cflow mcmlgo.c

1  main: char(), <mcmlmain.c 198>
2      ShowVersion: void*(), <mcmllio.c 49>
3          CenterStr: char*(), <mcmllio.c 28>
4              strlen: <>
5              strcpy: <>
6              strcat: <>
7          puts: <>
8      GetFnameFromArgv: void*(), <mcmlmain.c 150>
9          strcpy: 5
10     GetFile: struct*(), <mcmllio.c 94>
11         printf: <>
12         scanf: <>
13         strlen: 4
14         exit: <>
15         fopen: <>
16     CheckParm: void*(), <mcmllio.c 514>
17         ReadNumRuns: short(), <mcmllio.c 205>
18             FindDataLine: char*(), <mcmllio.c 184>
19                 fgets: <>
20                 printf: 11
21                 CheckChar: char(), <mcmllio.c 139>
22                     strlen: 4
23                     nrerror: void*(), <mcmlnr.c 19>
24                         fprintf: <>
25                         exit: 14
26                 KillChar: void*(), <mcmllio.c 123>
27                 CommentLine: char(), <mcmllio.c 165>
28                     strspn: <>
29                     strcspn: <>
30                 strcpy: 5
31                 nrerror: 23
32                 sscanf: <>
33             printf: 11
34         ReadParm: void*(), <mcmllio.c 425>
35             ReadFnameFormat: void*(), <mcmllio.c 225>
36                 FindDataLine: 18
37                 strcpy: 5
38                 nrerror: 23
39                 sscanf: 32
40                 toupper: <>
41             ReadNumPhotons: void*(), <mcmllio.c 243>
42                 FindDataLine: 18
43                 strcpy: 5
44                 nrerror: 23
45                 sscanf: 32

```

```
46      ReadDzDr: void*(), <mcmllo.c 260>
47          FindDataLine: 18
48          strcpy: 5
49          nrerror: 23
50          sscanf: 32
51      ReadNzNrNa: void*(), <mcmllo.c 276>
52          FindDataLine: 18
53          strcpy: 5
54          nrerror: 23
55          sscanf: 32
56      ReadNumLayers: void*(), <mcmllo.c 299>
57          FindDataLine: 18
58          strcpy: 5
59          nrerror: 23
60          sscanf: 32
61      ReadLayerSpecs: void*(), <mcmllo.c 375>
62          malloc: <>
63          nrerror: 23
64          ReadAmbient: void*(), <mcmllo.c 318>
65              FindDataLine: 18
66              strcpy: 5
67              sprintf: <>
68              nrerror: 23
69              sscanf: 32
70          ReadOneLayer: char(), <mcmllo.c 347>
71              FindDataLine: 18
72              strcpy: 5
73              sscanf: 32
74              sprintf: 67
75          CriticalAngle: void*(), <mcmllo.c 405>
76              sqrt: <>
77      FNameTaken: char(), <mcmllo.c 487>
78      NameInList: char(), <mcmllo.c 446>
79          strcmp: <>
80      AddNameToList: void*(), <mcmllo.c 459>
81          malloc: 62
82          strcpy: 5
83      sprintf: 67
84      free: <>
85      nrerror: 23
86      FreeFnameList: void*(), <mcmllo.c 500>
87          free: 84
88      rewind: <>
89      ReadNumRuns: 17
90      ReadParm: 34
91      DoOneRun: void*(), <mcmlmain.c 163>
92          InitOutputData: void*(), <mcmllo.c 546>
93              nrerror: 23
94          AllocMatrix: double**(), <mcmlnr.c 52>
95              malloc: 62
96              nrerror: 23
97          AllocVector: double*(), <mcmlnr.c 33>
98              malloc: 62
99              nrerror: 23
100     Rspecular: double(), <mcmlgo.c 117>
101     PunchTime: long(), <mcmlmain.c 60>
102         clock: <>
103         time: <>
```



```
104         sprintf: 67
105         puts: 7
106         strcpy: 5
107         difftime: <>
108     ReportStatus: void*(), <mcmlmain.c 122>
109         printf: 11
110     PredictDoneTime: void*(), <mcmlmain.c 95>
111         time: 103
112         localtime: <>
113         strftime: <>
114         printf: 11
115         PunchTime: 101
116     LaunchPhoton: void*(), <mcmlgo.c 143>
117         Rspecular: 100
118     HopDropSpin: void*(), <mcmlgo.c 726>
119         HopInGlass: void*(), <mcmlgo.c 675>
120             StepSizeInGlass: void*(), <mcmlgo.c 265>
121             Hop: void*(), <mcmlgo.c 246>
122             CrossOrNot: void*(), <mcmlgo.c 660>
123                 CrossUpOrNot: void*(), <mcmlgo.c 547>
124                     RFresnel: double(), <mcmlgo.c 421>
125                         sqrt: 76
126                     RandomNum: double(), <mcmlgo.c 83>
127                         time: 103
128                         ran3: float(), <mcmlgo.c 32>
129                     RecordR: void*(), <mcmlgo.c 480>
130                         sqrt: 76
131                         acos: <>
132                 CrossDnOrNot: void*(), <mcmlgo.c 609>
133                     RFresnel: 124
134                     RandomNum: 126
135                     RecordT: void*(), <mcmlgo.c 508>
136                         sqrt: 76
137                         acos: 131
138             HopDropSpinInTissue: void*(), <mcmlgo.c 706>
139                 StepSizeInTissue: void*(), <mcmlgo.c 295>
140                     RandomNum: 126
141                     log: <>
142             HitBoundary: char(), <mcmlgo.c 323>
143             Hop: 121
144             CrossOrNot: 122
145             Drop: void*(), <mcmlgo.c 365>
146                 sqrt: 76
147             Spin: void*(), <mcmlgo.c 204>
148                 SpinTheta: double(), <mcmlgo.c 176>
149                     RandomNum: 126
150                     sqrt: 76
151                     RandomNum: 126
152                     cos: <>
153                     fabs: <>
154         Roulette: void*(), <mcmlgo.c 395>
155             RandomNum: 126
156     ReportResult: void*(), <mcmlmain.c 133>
157         strcpy: 5
158         PunchTime: 101
159     SumScaleResult: void*(), <mcmllio.c 802>
160         Sum2DRd: void*(), <mcmllio.c 607>
161         Sum2DA: void*(), <mcmllio.c 652>
```

```
162         IzToLayer: short(), <mcml.io.c 637>
163         Sum2DTt: void*(), <mcml.io.c 677>
164         ScaleRdTt: void*(), <mcml.io.c 720>
165         sin: <>
166         ScaleA: void*(), <mcml.io.c 766>
167 WriteResult: void*(), <mcml.io.c 1091>
168     fopen: 15
169     nrerror: 23
170     toupper: 40
171 WriteVersion: void*(), <mcml.io.c 819>
172     fprintf: 24
173     fprintf: 24
174 WriteInParm: void*(), <mcml.io.c 833>
175     fprintf: 24
176 WriteRAT: void*(), <mcml.io.c 872>
177     fprintf: 24
178 WriteA_layer: void*(), <mcml.io.c 895>
179     fprintf: 24
180 WriteA_z: void*(), <mcml.io.c 1035>
181     fprintf: 24
182 WriteRd_r: void*(), <mcml.io.c 941>
183     fprintf: 24
184 WriteRd_a: void*(), <mcml.io.c 960>
185     fprintf: 24
186 WriteTt_r: void*(), <mcml.io.c 1054>
187     fprintf: 24
188 WriteTt_a: void*(), <mcml.io.c 1073>
189     fprintf: 24
190 WriteA_rz: void*(), <mcml.io.c 1008>
191     fprintf: 24
192 WriteRd_ra: void*(), <mcml.io.c 914>
193     fprintf: 24
194 WriteTt_ra: void*(), <mcml.io.c 980>
195     fprintf: 24
196     fclose: <>
197 FreeData: void*(), <mcml.io.c 581>
198     free: 84
199 FreeMatrix: void*(), <mcml.nr.c 86>
200     free: 84
201 FreeVector: void*(), <mcml.nr.c 77>
202     free: 84
203 fclose: 196
```

## Appendix B. Source Code of the Program mcml

The whole program is divided into several files. The file "mcml.h" is the header file, which defines data structures and some constants. The file "mcmlmain.c" contains the function `main()`. It also deals with the timings and status report. The file "mcmlio.c" reads or writes data from or to data files. The file "mcmlgo.c" does most of the Monte Carlo simulations. The file "mcmlnr.c" (nr stands for numerical recipes) contains several functions for dynamical data allocations and error report.

### B.1 mcml.h

```

1 /*****
2  * Copyright Univ. of Texas M.D. Anderson Cancer Center
3  * 1992.
4  *
5  * Monte Carlo simulation of photon distribution in
6  * multi-layered turbid media in ANSI Standard C.
7  ****
8  * Starting Date: 10/1991.
9  * Current Date: 6/1992.
10 *
11 * Lihong Wang, Ph. D.
12 * Steven L. Jacques, Ph. D.
13 * Laser Biology Research Laboratory - 17
14 * M.D. Anderson Cancer Center
15 * University of Texas
16 * 1515 Holcombe Blvd.
17 * Houston, TX 77030
18 * USA
19 *
20 * This program was based on:
21 * (1) The Pascal code written by Marleen Keijzer and
22 * Steven L. Jacques in this laboratory in 1989, which
23 * deals with multi-layered turbid media.
24 *
25 * (2) Algorithm for semi-infinite turbid medium by
26 * S.A. Prahl, M. Keijzer, S.L. Jacques, A.J. Welch,
27 * SPIE Institute Series Vol. IS 5 (1989), and by
28 * A.N. Witt, The Astrophysical journal Supplement
29 * Series 35, 1-6 (1977).
30 *
31 * Major modifications include:
32 * . Conform to ANSI Standard C.
33 * . Removal of limit on number of array elements,
34 * . because arrays in this program are dynamically
35 * . allocated. This means that the program can accept
36 * . any number of layers or gridlines as long as the
37 * . memory permits.
38 * . Avoiding global variables whenever possible. This
39 * . program has not used global variables so far.
40 * . Grouping variables logically using structures.

```

```

41 *      . Top-down design, keep each subroutine clear &
42 *      short.
43 *      . Reflectance and transmittance are angularly
44 *      resolved.
45 ****
46 * General Naming Conventions:
47 * Preprocessor names: all capital letters,
48 *     e.g. #define PREPROCESSORS
49 * Globals: first letter of each word is capital, no
50 *     underscores,
51 *     e.g. short GlobalVar;
52 * Dummy variables: first letter of each word is capital,
53 *     and words are connected by underscores,
54 *     e.g. void NiceFunction(char Dummy_Var);
55 * Local variables: all lower cases, words are connected
56 *     by underscores,
57 *     e.g. short local_var;
58 * Function names or data types: same as Globals.
59 *
60 ****
61 * Dimension of length: cm.
62 *
63 ****/
64
65 #include <math.h>
66 #include <stdlib.h>
67 #include <stdio.h>
68 #include <stddef.h>
69 #include <time.h>
70 #include <string.h>
71 #include <ctype.h>
72
73 #define PI 3.1415926
74 #define WEIGHT 1E-4      /* Critical weight for roulette. */
75 #define CHANCE 0.1      /* Chance of roulette survival. */
76 #define STRLEN 256      /* String length. */
77
78 #define Boolean char
79
80 #define SIGN(x) ((x)>=0 ? 1:-1)
81
82 /***** Structures *****/
83
84 /****
85 * Structure used to describe a photon packet.
86 ****/
87 typedef struct {
88     double x, y ,z;      /* Cartesian coordinates.[cm] */
89     double ux, uy, uz; /* directional cosines of a photon. */
90     double w;           /* weight. */
91     Boolean dead;       /* 1 if photon is terminated. */
92     short layer;        /* index to layer where the photon */
93                       /* packet resides. */
94     double s;           /* current step size. [cm]. */
95     double sleft;       /* step size left. dimensionless [-]. */
96 } PhotonStruct;
97
98 /****

```

```

99  * Structure used to describe the geometry and optical
100 * properties of a layer.
101 * z0 and z1 are the z coordinates for the upper boundary
102 * and lower boundary respectively.
103 *
104 * cos_crit0 and cos_crit1 are the cosines of the
105 * critical angle of total internal reflection for the
106 * upper boundary and lower boundary respectively.
107 * They are set to zero if no total internal reflection
108 * exists.
109 * They are used for computation speed.
110 ****/
111 typedef struct {
112     double z0, z1;      /* z coordinates of a layer. [cm] */
113     double n;          /* refractive index of a layer. */
114     double mua;        /* absorption coefficient. [1/cm] */
115     double mus;        /* scattering coefficient. [1/cm] */
116     double g;          /* anisotropy. */
117
118     double cos_crit0, cos_crit1;
119 } LayerStruct;
120
121 /****
122 * Input parameters for each independent run.
123 *
124 * z and r are for the cylindrical coordinate system. [cm]
125 * a is for the angle alpha between the photon exiting
126 * direction and the surface normal. [radian]
127 *
128 * The grid line separations in z, r, and alpha
129 * directions are dz, dr, and da respectively. The numbers
130 * of grid lines in z, r, and alpha directions are
131 * nz, nr, and na respectively.
132 *
133 * The member layerspecs will point to an array of
134 * structures which store parameters of each layer.
135 * This array has (number_layers + 2) elements. One
136 * element is for a layer.
137 * The layers 0 and (num_layers + 1) are for top ambient
138 * medium and the bottom ambient medium respectively.
139 ****/
140 typedef struct {
141     char    out_fname[STRLEN]; /* output file name. */
142     char    out_fformat;      /* output file format. */
143                                     /* 'A' for ASCII, */
144                                     /* 'B' for binary. */
145     long    num_photons;      /* to be traced. */
146     double  Wth;              /* play roulette if photon */
147                                     /* weight < Wth.*/
148
149     double  dz;               /* z grid separation.[cm] */
150     double  dr;               /* r grid separation.[cm] */
151     double  da;               /* alpha grid separation. */
152                                     /* [radian] */
153     short   nz;               /* array range 0..nz-1. */
154     short   nr;               /* array range 0..nr-1. */
155     short   na;               /* array range 0..na-1. */
156

```

```

157 short num_layers;          /* number of layers. */
158 LayerStruct * layerspecs; /* layer parameters. */
159 } InputStruct;
160
161 /****
162 * Structures for scoring physical quantities.
163 * z and r represent z and r coordinates of the
164 * cylindrical coordinate system. [cm]
165 * a is the angle alpha between the photon exiting
166 * direction and the normal to the surfaces. [radian]
167 * See comments of the InputStruct.
168 * See manual for the physical quantities.
169 ****/
170 typedef struct {
171     double    Rsp;          /* specular reflectance. [-] */
172     double ** Rd_ra;        /* 2D distribution of diffuse */
173                             /* reflectance. [1/(cm2 sr)] */
174     double *  Rd_r;         /* 1D radial distribution of diffuse */
175                             /* reflectance. [1/cm2] */
176     double *  Rd_a;         /* 1D angular distribution of diffuse */
177                             /* reflectance. [1/sr] */
178     double    Rd;          /* total diffuse reflectance. [-] */
179
180     double ** A_rz;         /* 2D probability density in turbid */
181                             /* media over r & z. [1/cm3] */
182     double *  A_z;         /* 1D probability density over z. */
183                             /* [1/cm] */
184     double *  A_l;         /* each layer's absorption */
185                             /* probability. [-] */
186     double    A;           /* total absorption probability. [-] */
187
188     double ** Tt_ra;        /* 2D distribution of total */
189                             /* transmittance. [1/(cm2 sr)] */
190     double *  Tt_r;         /* 1D radial distribution of */
191                             /* transmittance. [1/cm2] */
192     double *  Tt_a;         /* 1D angular distribution of */
193                             /* transmittance. [1/sr] */
194     double    Tt;          /* total transmittance. [-] */
195 } OutStruct;
196
197 /*****
198 * Routine prototypes for dynamic memory allocation and
199 * release of arrays and matrices.
200 * Modified from Numerical Recipes in C.
201 *****/
202 double *AllocVector(short, short);
203 double **AllocMatrix(short, short,short, short);
204 void FreeVector(double *, short, short);
205 void FreeMatrix(double **, short, short, short, short);
206 void nrerror(char *);

```

**B.2 mcmlmain.c**

```
1 /*****
2  * Copyright Univ. of Texas M.D. Anderson Cancer Center
3  * 1992.
4  *
5  * main program for Monte Carlo simulation of photon
6  * distribution in multi-layered turbid media.
7  *
8  *****/
9
10 /****
11  * THINKCProfiler is defined to generate profiler calls in
12  * Think C. If 1, remember to turn on "Generate profiler
13  * calls" in the options menu.
14  *****/
15 #define THINKCProfiler 0
16
17 /* GNU cc does not support difftime() and CLOCKS_PER_SEC.*/
18 #define GNUCC 0
19
20 #if THINKCProfiler
21 #include <profile.h>
22 #include <console.h>
23 #endif
24
25 #include "mcml.h"
26
27 /* Declare before they are used in main(). */
28 FILE *GetFile(char *);
29 short ReadNumRuns(FILE* );
30 void ReadParm(FILE* , InputStruct * );
31 void CheckParm(FILE* , InputStruct * );
32 void InitOutputData(InputStruct, OutStruct *);
33 void FreeData(InputStruct, OutStruct *);
34 double Rspecular(LayerStruct * );
35 void LaunchPhoton(double, LayerStruct *, PhotonStruct *);
36 void HopDropSpin(InputStruct *, PhotonStruct *, OutStruct *);
37 void SumScaleResult(InputStruct, OutStruct *);
38 void WriteResult(InputStruct, OutStruct, char *);
39
40
41 /*****
42  * If F = 0, reset the clock and return 0.
43  *
44  * If F = 1, pass the user time to Msg and print Msg on
45  * screen, return the real time since F=0.
46  *
47  * If F = 2, same as F=1 except no printing.
48  *
49  * Note that clock() and time() return user time and real
50  * time respectively.
51  * User time is whatever the system allocates to the
52  * running of the program;
53  * real time is wall-clock time. In a time-shared system,
54  * they need not be the same.
```

```

55  *
56  *  clock() only hold 16 bit integer, which is about 32768
57  *  clock ticks.
58  ****/
59  time_t PunchTime(char F, char *Msg)
60  {
61  #if GNUCC
62  return(0);
63 #else
64  static clock_t ut0; /* user time reference. */
65  static time_t  rt0; /* real time reference. */
66  double secs;
67  char s[STRLEN];
68
69  if(F==0) {
70  ut0 = clock();
71  rt0 = time(NULL);
72  return(0);
73  }
74  else if(F==1) {
75  secs = (clock() - ut0)/(double)CLOCKS_PER_SEC;
76  if (secs<0) secs=0; /* clock() can overflow. */
77  sprintf(s, "User time: %8.0lf sec = %8.2lf hr.  %s\n",
78  secs, secs/3600.0, Msg);
79  puts(s);
80  strcpy(Msg, s);
81  return(difftime(time(NULL), rt0));
82  }
83  else if(F==2) return(difftime(time(NULL), rt0));
84  else return(0);
85 #endif
86 }
87
88 /*****
89  *  Print the current time and the estimated finishing time.
90  *
91  *  P1 is the number of computed photon packets.
92  *  Pt is the total number of photon packets.
93  *****/
94  void PredictDoneTime(long P1, long Pt)
95  {
96  time_t now, done_time;
97  struct tm *date;
98  char s[80];
99
100  now = time(NULL);
101  date = localtime(&now);
102  strftime(s, 80, "%H:%M %x", date);
103  printf("Now %s, ", s);
104
105  done_time = now +
106  (time_t) (PunchTime(2, "")*(Pt-P1)/(double)P1);
107  date = localtime(&done_time);
108  strftime(s, 80, "%H:%M %x", date);
109  printf("End %s\n", s);
110 }
111
112 /*****

```



```
113 * Report estimated time, number of photons and runs left
114 * after calculating 10 photons or every 1/10 of total
115 * number of photons.
116 *
117 * Num_Runs is the number of runs left.
118 * Pi is the index to the current photon, counting down.
119 * Pt is the total number of photons.
120 ****/
121 void ReportStatus(short Num_Runs, long Pi, long Pt)
122 {
123     if(Pt-Pi == 10 || Pi*10%Pt == 0 && Pi != Pt) {
124         printf("%ld photons & %hd runs left, ", Pi, Num_Runs);
125         PredictDoneTime(Pt-Pi, Pt);
126     }
127 }
128
129 /*****
130 * Report time and write results.
131 *****/
132 void ReportResult(InputStruct In_Parm, OutStruct Out_Parm)
133 {
134     char time_report[STRLEN];
135
136     strcpy(time_report, " Simulation time of this run.");
137     PunchTime(1, time_report);
138
139     SumScaleResult(In_Parm, &Out_Parm);
140     WriteResult(In_Parm, Out_Parm, time_report);
141 }
142
143 /*****
144 * Get the file name of the input data file from the
145 * argument to the command line.
146 *****/
147 void GetFnameFromArgv(int argc,
148                       char * argv[],
149                       char * input_filename)
150 {
151     if(argc>=2) { /* filename in command line */
152         strcpy(input_filename, argv[1]);
153     }
154     else
155         input_filename[0] = '\0';
156 }
157
158
159 /*****
160 * Execute Monte Carlo simulation for one independent run.
161 *****/
162 void DoOneRun(short NumRuns, InputStruct *In_Ptr)
163 {
164     register long i_photon;
165     /* index to photon. register for speed.*/
166     OutStruct out_parm; /* distribution of photons.*/
167     PhotonStruct photon;
168
169 #if THINKCProfiler
170     InitProfile(200,200); cecho2file("prof.rpt",0, stdout);
```

```
171 #endif
172
173   InitOutputData(*In_Ptr, &out_parm);
174   out_parm.Rsp = Rspecular(In_Ptr->layerspecs);
175   i_photon = In_Ptr->num_photons;
176   PunchTime(0, "");
177
178   do {
179     ReportStatus(NumRuns, i_photon, In_Ptr->num_photons);
180     LaunchPhoton(out_parm.Rsp, In_Ptr->layerspecs, &photon);
181     do HopDropSpin(In_Ptr, &photon, &out_parm);
182     while (!photon.dead);
183   } while(--i_photon);
184
185 #if THINKCProfiler
186   exit(0);
187 #endif
188
189   ReportResult(*In_Ptr, out_parm);
190   FreeData(*In_Ptr, &out_parm);
191 }
192
193 /*****
194  * The argument to the command line is filename, if any.
195  * Macintosh does not support command line.
196  *****/
197 char main(int argc, char *argv[])
198 {
199   char input_filename[STRLEN];
200   FILE *input_file_ptr;
201   short num_runs; /* number of independent runs. */
202   InputStruct in_parm;
203
204   ShowVersion("Version 1.1, 1992");
205   GetFnameFromArgv(argc, argv, input_filename);
206   input_file_ptr = GetFile(input_filename);
207   CheckParm(input_file_ptr, &in_parm);
208   num_runs = ReadNumRuns(input_file_ptr);
209
210   while(num_runs-- > 0) {
211     ReadParm(input_file_ptr, &in_parm);
212     DoOneRun(num_runs, &in_parm);
213   }
214
215   fclose(input_file_ptr);
216   return(0);
217 }
```

**B.3 mcml.io.c**

```

1  /*****
2  * Copyright Univ. of Texas M.D. Anderson Cancer Center
3  * 1992.
4  *
5  * Input/output of data.
6  ****/
7
8  #include "mcml.h"
9
10 /*****
11 * Structure used to check against duplicated file names.
12 ****/
13 struct NameList {
14     char name[STRLEN];
15     struct NameList * next;
16 };
17
18 typedef struct NameList NameNode;
19 typedef NameNode * NameLink;
20
21
22 /*****
23 * Center a string according to the column width.
24 ****/
25 char * CenterStr(short Wid,
26                  char * InStr,
27                  char * OutStr)
28 {
29     size_t nspaces; /* number of spaces to be filled */
30                    /* before InStr. */
31
32     nspaces = (Wid - strlen(InStr))/2;
33     if(nspaces<0) nspaces = 0;
34
35     strcpy(OutStr, "");
36     while(nspaces--) strcat(OutStr, " ");
37
38     strcat(OutStr, InStr);
39
40     return(OutStr);
41 }
42
43 /*****
44 * Print some messages before starting simulation.
45 * e.g. author, address, program version, year.
46 ****/
47 #define COLWIDTH 80
48 void ShowVersion(char *version)
49 {
50     char str[STRLEN];
51
52     CenterStr(COLWIDTH,
53              "mcml - Monte Carlo Simulation of Multi-layered Turbid Media",
54              str);

```

```

55 puts(str);
56 puts("");
57
58 CenterStr(COLWIDTH, "Lihong Wang, Ph. D.", str);
59 puts(str);
60
61 CenterStr(COLWIDTH, "Steven L. Jacques, Ph. D.", str);
62 puts(str);
63
64 CenterStr(COLWIDTH,
65     "Laser Biology Research Laboratory - Box 17",str);
66 puts(str);
67
68 CenterStr(COLWIDTH, "M.D. Anderson Cancer Center", str);
69 puts(str);
70
71 CenterStr(COLWIDTH, "University of Texas", str);
72 puts(str);
73
74 CenterStr(COLWIDTH, "Houston, TX 77030", str);
75 puts(str);
76
77 CenterStr(COLWIDTH, "Fax: (713)792-3995", str);
78 puts(str);
79 puts("");
80
81 CenterStr(COLWIDTH, version, str);
82 puts(str);
83 puts("\n\n\n\n");
84 }
85 #undef COLWIDTH
86
87 /*****
88 * Get a filename and open it for reading, retry until
89 * the file can be opened. '.' terminates the program.
90 *
91 * If Fname != NULL, try Fname first.
92 *****/
93 FILE *GetFile(char *Fname)
94 {
95     FILE * file=NULL;
96     Boolean firsttime=1;
97
98     do {
99         if(firsttime && Fname[0]!='\0') {
100             /* use the filename from command line */
101             firsttime = 0;
102         }
103         else {
104             printf("Input filename(or . to exit):");
105             scanf("%s", Fname);
106             firsttime = 0;
107         }
108
109         if(strlen(Fname) == 1 && Fname[0] == '.')
110             exit(1); /* exit if no filename entered. */
111
112         file = fopen(Fname, "r");

```

```
113 } while(file == NULL);
114
115 return(file);
116 }
117
118 /*****
119 * Kill the ith char (counting from 0), push the following
120 * chars forward by one.
121 *****/
122 void KillChar(size_t i, char * Str)
123 {
124     size_t sl = strlen(Str);
125
126     for(;i<sl;i++) Str[i] = Str[i+1];
127 }
128
129 /*****
130 * Eliminate the chars in a string which are not printing
131 * chars or spaces.
132 *
133 * Spaces include ' ', '\f', '\t' etc.
134 *
135 * Return 1 if no nonprinting chars found, otherwise
136 * return 0.
137 *****/
138 Boolean CheckChar(char * Str)
139 {
140     Boolean found = 0; /* found bad char. */
141     size_t sl = strlen(Str);
142     size_t i=0;
143
144     while(i<sl)
145         if (Str[i]<0 || Str[i]>255)
146             nrerror("Non-ASCII file\n");
147         else if(isprint(Str[i]) || isspace(Str[i]))
148             i++;
149         else {
150             found = 1;
151             KillChar(i, Str);
152             sl--;
153         }
154
155     return(found);
156 }
157
158 /*****
159 * Return 1 if this line is a comment line in which the
160 * first non-space character is "#".
161 *
162 * Also return 1 if this line is space line.
163 *****/
164 Boolean CommentLine(char *Buf)
165 {
166     size_t spn, cspn;
167
168     spn = strstr(Buf, " \t");
169     /* length spanned by space or tab chars. */
170
```

```

171  cspn = strcspn(Buf, "#\n");
172  /* length before the 1st # or return. */
173
174  if(spn == cspn) /* comment line or space line. */
175      return(1);
176  else /* the line has data. */
177      return(0);
178 }
179
180 /*****
181  * Skip space or comment lines and return a data line only.
182  *****/
183 char * FindDataLine(FILE *File_Ptr)
184 {
185     char buf[STRLEN];
186
187     buf[0] = '\0';
188     do { /* skip space or comment lines. */
189         if(fgets(buf, 255, File_Ptr) == NULL) {
190             printf("Incomplete data\n");
191             buf[0]='\0';
192             break;
193         }
194         else
195             CheckChar(buf);
196     } while(CommentLine(buf));
197
198     return(buf);
199 }
200
201 /*****
202  * Skip file version, then read number of runs.
203  *****/
204 short ReadNumRuns(FILE* File_Ptr)
205 {
206     char buf[STRLEN];
207     short n=0;
208
209     FindDataLine(File_Ptr); /* skip file version. */
210
211     strcpy(buf, FindDataLine(File_Ptr));
212     if(buf[0]!='\0') nrerror("Reading number of runs\n");
213     sscanf(buf, "%hd",&n);
214     return(n);
215 }
216
217
218 /*****
219  * Read the file name and the file format.
220  *
221  * The file format can be either A for ASCII or B for
222  * binary.
223  *****/
224 void ReadFnameFormat(FILE *File_Ptr, InputStruct *In_Ptr)
225 {
226     char buf[STRLEN];
227
228     /*** read in file name and format. ***/

```

```

229 strcpy(buf, FindDataLine(File_Ptr));
230 if(buf[0]!='\0')
231     nrerror("Reading file name and format.\n");
232 sscanf(buf, "%s %c",
233     In_Ptr->out_fname, &(In_Ptr->out_fformat) );
234 if(toupper(In_Ptr->out_fformat) != 'B')
235     In_Ptr->out_fformat = 'A';
236 }
237
238
239 /*****
240 * Read the number of photons.
241 *****/
242 void ReadNumPhotons(FILE *File_Ptr, InputStruct *In_Ptr)
243 {
244     char buf[STRLEN];
245
246     /** read in number of photons. **/
247     strcpy(buf, FindDataLine(File_Ptr));
248     if(buf[0]!='\0')
249         nrerror("Reading number of photons.\n");
250     sscanf(buf, "%ld", &In_Ptr->num_photons);
251     if(In_Ptr->num_photons<=0)
252         nrerror("Nonpositive number of photons.\n");
253 }
254
255
256 /*****
257 * Read the members dz and dr.
258 *****/
259 void ReadDzDr(FILE *File_Ptr, InputStruct *In_Ptr)
260 {
261     char buf[STRLEN];
262
263     /** read in dz, dr. **/
264     strcpy(buf, FindDataLine(File_Ptr));
265     if(buf[0]!='\0') nrerror("Reading dz, dr.\n");
266     sscanf(buf, "%lf%lf", &In_Ptr->dz, &In_Ptr->dr);
267     if(In_Ptr->dz<=0) nrerror("Nonpositive dz.\n");
268     if(In_Ptr->dr<=0) nrerror("Nonpositive dr.\n");
269 }
270
271
272 /*****
273 * Read the members nz, nr, na.
274 *****/
275 void ReadNzNrNa(FILE *File_Ptr, InputStruct *In_Ptr)
276 {
277     char buf[STRLEN];
278
279     /** read in number of dz, dr, da. **/
280     strcpy(buf, FindDataLine(File_Ptr));
281     if(buf[0]!='\0')
282         nrerror("Reading number of dz, dr, da's.\n");
283     sscanf(buf, "%hd%hd%hd",
284         &In_Ptr->nz, &In_Ptr->nr, &In_Ptr->na);
285     if(In_Ptr->nz<=0)
286         nrerror("Nonpositive number of dz's.\n");

```

```

287  if(In_Ptr->nr<=0)
288      nrerror("Nonpositive number of dr's.\n");
289  if(In_Ptr->na<=0)
290      nrerror("Nonpositive number of da's.\n");
291  In_Ptr->da = 0.5*PI/In_Ptr->na;
292  }
293
294
295  /*****
296   * Read the number of layers.
297   *****/
298 void ReadNumLayers(FILE *File_Ptr, InputStruct *In_Ptr)
299 {
300     char buf[STRLEN];
301
302     /** read in number of layers. **/
303     strcpy(buf, FindDataLine(File_Ptr));
304     if(buf[0]!='\0')
305         nrerror("Reading number of layers.\n");
306     sscanf(buf, "%hd", &In_Ptr->num_layers);
307     if(In_Ptr->num_layers<=0)
308         nrerror("Nonpositive number of layers.\n");
309 }
310
311
312 /*****
313  * Read the refractive index n of the ambient.
314  *****/
315 void ReadAmbient(FILE *File_Ptr,
316                 LayerStruct * Layer_Ptr,
317                 char *side)
318 {
319     char buf[STRLEN], msg[STRLEN];
320     double n;
321
322     strcpy(buf, FindDataLine(File_Ptr));
323     if(buf[0]!='\0') {
324         sprintf(msg, "Reading n of %s ambient.\n", side);
325         nrerror(msg);
326     }
327
328     sscanf(buf, "%lf", &n );
329     if(n<=0) nrerror("Wrong n.\n");
330     Layer_Ptr->n = n;
331 }
332
333
334 /*****
335  * Read the parameters of one layer.
336  *
337  * Return 1 if error detected.
338  * Return 0 otherwise.
339  *
340  * *Z_Ptr is the z coordinate of the current layer, which
341  * is used to convert thickness of layer to z coordinates
342  * of the two boundaries of the layer.
343  *****/
344 Boolean ReadOneLayer(FILE *File_Ptr,

```



```

345         LayerStruct * Layer_Ptr,
346         double *Z_Ptr)
347 {
348     char buf[STRLEN], msg[STRLEN];
349     double d, n, mua, mus, g; /* d is thickness. */
350
351     strcpy(buf, FindDataLine(File_Ptr));
352     if(buf[0]!='\0') return(1); /* error. */
353
354     sscanf(buf, "%lf%lf%lf%lf%lf", &n, &mua, &mus, &g, &d);
355     if(d<0 || n<=0 || mua<0 || mus<0 || g<0 || g>1)
356         return(1); /* error. */
357
358     Layer_Ptr->n = n;
359     Layer_Ptr->mua = mua;
360     Layer_Ptr->mus = mus;
361     Layer_Ptr->g = g;
362     Layer_Ptr->z0 = *Z_Ptr;
363     *Z_Ptr += d;
364     Layer_Ptr->z1 = *Z_Ptr;
365
366     return(0);
367 }
368
369 /*****
370 * Read the parameters of one layer at a time.
371 *****/
372 void ReadLayerSpecs(FILE *File_Ptr,
373                    short Num_Layers,
374                    LayerStruct ** Layerspecs_PP)
375 {
376     char msg[STRLEN];
377     short i=0;
378     double z = 0.0; /* z coordinate of the current layer. */
379
380     /* Allocate an array for the layer parameters. */
381     /* layer 0 and layer Num_Layers + 1 are for ambient. */
382     *Layerspecs_PP = (LayerStruct *)
383         malloc((unsigned) (Num_Layers+2)*sizeof(LayerStruct));
384     if (!(*Layerspecs_PP))
385         nrerror("allocation failure in ReadLayerSpecs()");
386
387     ReadAmbient(File_Ptr, &((*Layerspecs_PP)[i]), "top");
388     for(i=1; i<=Num_Layers; i++)
389         if(ReadOneLayer(File_Ptr, &((*Layerspecs_PP)[i]), &z)) {
390             sprintf(msg, "Error reading %hd of %hd layers\n",
391                     i, Num_Layers);
392             nrerror(msg);
393         }
394     ReadAmbient(File_Ptr, &((*Layerspecs_PP)[i]), "bottom");
395 }
396
397 /*****
398 * Compute the critical angles for total internal
399 * reflection according to the relative refractive index
400 * of the layer.
401 * All layers are processed.
402 *****/

```

```

403 void CriticalAngle( short Num_Layers,
404                    LayerStruct ** Layerspecs_PP)
405 {
406     short i=0;
407     double n1, n2;
408
409     for(i=1; i<=Num_Layers; i++) {
410         n1 = (*Layerspecs_PP)[i].n;
411         n2 = (*Layerspecs_PP)[i-1].n;
412         (*Layerspecs_PP)[i].cos_crit0 = n1>n2 ?
413             sqrt(1.0 - n2*n2/(n1*n1)) : 0.0;
414
415         n2 = (*Layerspecs_PP)[i+1].n;
416         (*Layerspecs_PP)[i].cos_crit1 = n1>n2 ?
417             sqrt(1.0 - n2*n2/(n1*n1)) : 0.0;
418     }
419 }
420
421 /*****
422  * Read in the input parameters for one run.
423  *****/
424 void ReadParm(FILE* File_Ptr, InputStruct * In_Ptr)
425 {
426     char buf[STRLEN];
427
428     In_Ptr->Wth = WEIGHT;
429
430     ReadFnameFormat(File_Ptr, In_Ptr);
431     ReadNumPhotons(File_Ptr, In_Ptr);
432     ReadDzDr(File_Ptr, In_Ptr);
433     ReadNzNrNa(File_Ptr, In_Ptr);
434     ReadNumLayers(File_Ptr, In_Ptr);
435
436     ReadLayerSpecs(File_Ptr, In_Ptr->num_layers,
437                   &In_Ptr->layerspecs);
438     CriticalAngle(In_Ptr->num_layers, &In_Ptr->layerspecs);
439 }
440
441 /*****
442  * Return 1, if the name in the name list.
443  * Return 0, otherwise.
444  *****/
445 Boolean NameInList(char *Name, NameLink List)
446 {
447     while (List != NULL) {
448         if(strcmp(Name, List->name) == 0)
449             return(1);
450         List = List->next;
451     };
452     return(0);
453 }
454
455 /*****
456  * Add the name to the name list.
457  *****/
458 void AddNameToList(char *Name, NameLink * List_Ptr)
459 {
460     NameLink list = *List_Ptr;

```

```

461
462 if(list == NULL) { /* first node. */
463     *List_Ptr = list = (NameLink)malloc(sizeof(NameNode));
464     strcpy(list->name, Name);
465     list->next = NULL;
466 }
467 else { /* subsequent nodes. */
468     /* Move to the last node. */
469     while(list->next != NULL)
470         list = list->next;
471
472     /* Append a node to the list. */
473     list->next = (NameLink)malloc(sizeof(NameNode));
474     list = list->next;
475     strcpy(list->name, Name);
476     list->next = NULL;
477 }
478 }
479
480 /*****
481 * Check against duplicated file names.
482 *
483 * A linked list is set up to store the file names used
484 * in this input data file.
485 *****/
486 Boolean FnameTaken(char *fname, NameLink * List_Ptr)
487 {
488     if(NameInList(fname, *List_Ptr))
489         return(1);
490     else {
491         AddNameToList(fname, List_Ptr);
492         return(0);
493     }
494 }
495
496 /*****
497 * Free each node in the file name list.
498 *****/
499 void FreeFnameList(NameLink List)
500 {
501     NameLink next;
502
503     while(List != NULL) {
504         next = List->next;
505         free(List);
506         List = next;
507     }
508 }
509
510 /*****
511 * Check the input parameters for each run.
512 *****/
513 void CheckParm(FILE* File_Ptr, InputStruct * In_Ptr)
514 {
515     short i_run;
516     short num_runs; /* number of independent runs. */
517     NameLink head = NULL;
518     Boolean name_taken; /* output files share the same */

```

```

519             /* file name.*/
520     char msg[STRLEN];
521
522     num_runs = ReadNumRuns(File_Ptr);
523     for(i_run=1; i_run<=num_runs; i_run++) {
524         printf("Checking input data for run %hd\n", i_run);
525         ReadParm(File_Ptr, In_Ptr);
526
527         name_taken = FnameTaken(In_Ptr->out_fname, &head);
528         if(name_taken)
529             sprintf(msg, "file name %s duplicated.\n",
530                     In_Ptr->out_fname);
531
532         free(In_Ptr->layerspecs);
533         if(name_taken) nrerror(msg);
534     }
535     FreeFnameList(head);
536     rewind(File_Ptr);
537 }
538
539
540 /*****
541  * Allocate the arrays in OutStruct for one run, and
542  * array elements are automatically initialized to zeros.
543  *****/
544 void InitOutputData(InputStruct In_Parm,
545                    OutStruct * Out_Ptr)
546 {
547     short nz = In_Parm.nz;
548     short nr = In_Parm.nr;
549     short na = In_Parm.na;
550     short nl = In_Parm.num_layers;
551     /* remember to use nl+2 because of 2 for ambient. */
552
553     if(nz<=0 || nr<=0 || na<=0 || nl<=0)
554         nrerror("Wrong grid parameters.\n");
555
556     /* Init pure numbers. */
557     Out_Ptr->Rsp = 0.0;
558     Out_Ptr->Rd   = 0.0;
559     Out_Ptr->A    = 0.0;
560     Out_Ptr->Tt   = 0.0;
561
562     /* Allocate the arrays and the matrices. */
563     Out_Ptr->Rd_ra = AllocMatrix(0,nr-1,0,na-1);
564     Out_Ptr->Rd_r  = AllocVector(0,nr-1);
565     Out_Ptr->Rd_a  = AllocVector(0,na-1);
566
567     Out_Ptr->A_rz  = AllocMatrix(0,nr-1,0,nz-1);
568     Out_Ptr->A_z   = AllocVector(0,nz-1);
569     Out_Ptr->A_l   = AllocVector(0,nl+1);
570
571     Out_Ptr->Tt_ra = AllocMatrix(0,nr-1,0,na-1);
572     Out_Ptr->Tt_r  = AllocVector(0,nr-1);
573     Out_Ptr->Tt_a  = AllocVector(0,na-1);
574 }
575
576 /*****

```

```

577 * Undo what InitOutputData did.
578 * i.e. free the data allocations.
579 ****/
580 void FreeData(InputStruct In_Parm, OutStruct * Out_Ptr)
581 {
582     short nz = In_Parm.nz;
583     short nr = In_Parm.nr;
584     short na = In_Parm.na;
585     short nl = In_Parm.num_layers;
586     /* remember to use nl+2 because of 2 for ambient. */
587
588     free(In_Parm.layerspecs);
589
590     FreeMatrix(Out_Ptr->Rd_ra, 0,nr-1,0,na-1);
591     FreeVector(Out_Ptr->Rd_r, 0,nr-1);
592     FreeVector(Out_Ptr->Rd_a, 0,na-1);
593
594     FreeMatrix(Out_Ptr->A_rz, 0, nr-1, 0,nz-1);
595     FreeVector(Out_Ptr->A_z, 0, nz-1);
596     FreeVector(Out_Ptr->A_l, 0,nl+1);
597
598     FreeMatrix(Out_Ptr->Tt_ra, 0,nr-1,0,na-1);
599     FreeVector(Out_Ptr->Tt_r, 0,nr-1);
600     FreeVector(Out_Ptr->Tt_a, 0,na-1);
601 }
602
603 /*****
604 * Get 1D array elements by summing the 2D array elements.
605 *****/
606 void Sum2DRd(InputStruct In_Parm, OutStruct * Out_Ptr)
607 {
608     short nr = In_Parm.nr;
609     short na = In_Parm.na;
610     short ir,ia;
611     double sum;
612
613     for(ir=0; ir<nr; ir++) {
614         sum = 0.0;
615         for(ia=0; ia<na; ia++) sum += Out_Ptr->Rd_ra[ir][ia];
616         Out_Ptr->Rd_r[ir] = sum;
617     }
618
619     for(ia=0; ia<na; ia++) {
620         sum = 0.0;
621         for(ir=0; ir<nr; ir++) sum += Out_Ptr->Rd_ra[ir][ia];
622         Out_Ptr->Rd_a[ia] = sum;
623     }
624
625     sum = 0.0;
626     for(ir=0; ir<nr; ir++) sum += Out_Ptr->Rd_r[ir];
627     Out_Ptr->Rd = sum;
628 }
629
630 /*****
631 * Return the index to the layer according to the index
632 * to the grid line system in z direction (Iz).
633 *
634 * Use the center of box.

```

```

635 ****/
636 short IzToLayer(short Iz, InputStruct In_Parm)
637 {
638     short i=1;    /* index to layer. */
639     short num_layers = In_Parm.num_layers;
640     double dz = In_Parm.dz;
641
642     while( (Iz+0.5)*dz >= In_Parm.layerspecs[i].z1
643         && i<num_layers) i++;
644
645     return(i);
646 }
647
648 /*****
649 * Get 1D array elements by summing the 2D array elements.
650 *****/
651 void Sum2DA(InputStruct In_Parm, OutStruct * Out_Ptr)
652 {
653     short nz = In_Parm.nz;
654     short nr = In_Parm.nr;
655     short iz,ir;
656     double sum;
657
658     for(iz=0; iz<nz; iz++) {
659         sum = 0.0;
660         for(ir=0; ir<nr; ir++) sum += Out_Ptr->A_rz[ir][iz];
661         Out_Ptr->A_z[iz] = sum;
662     }
663
664     sum = 0.0;
665     for(iz=0; iz<nz; iz++) {
666         sum += Out_Ptr->A_z[iz];
667         Out_Ptr->A_l[IzToLayer(iz, In_Parm)]
668             += Out_Ptr->A_z[iz];
669     }
670     Out_Ptr->A = sum;
671 }
672
673 /*****
674 * Get 1D array elements by summing the 2D array elements.
675 *****/
676 void Sum2DTt(InputStruct In_Parm, OutStruct * Out_Ptr)
677 {
678     short nr = In_Parm.nr;
679     short na = In_Parm.na;
680     short ir,ia;
681     double sum;
682
683     for(ir=0; ir<nr; ir++) {
684         sum = 0.0;
685         for(ia=0; ia<na; ia++) sum += Out_Ptr->Tt_ra[ir][ia];
686         Out_Ptr->Tt_r[ir] = sum;
687     }
688
689     for(ia=0; ia<na; ia++) {
690         sum = 0.0;
691         for(ir=0; ir<nr; ir++) sum += Out_Ptr->Tt_ra[ir][ia];
692         Out_Ptr->Tt_a[ia] = sum;

```

```

693 }
694
695 sum = 0.0;
696 for(ir=0; ir<nr; ir++) sum += Out_Ptr->Tt_r[ir];
697 Out_Ptr->Tt = sum;
698 }
699
700 /*****
701 * Scale Rd and Tt properly.
702 *
703 * "a" stands for angle alpha.
704 ****
705 * Scale Rd(r,a) and Tt(r,a) by
706 *   (area perpendicular to photon direction)
707 *   x(solid angle)x(No. of photons).
708 * or
709 *   [2*PI*r*dr*cos(a)]x[2*PI*sin(a)*da]x[No. of photons]
710 * or
711 *   [2*PI*PI*dr*da*r*sin(2a)]x[No. of photons]
712 ****
713 * Scale Rd(r) and Tt(r) by
714 *   (area on the surface)x(No. of photons).
715 ****
716 * Scale Rd(a) and Tt(a) by
717 *   (solid angle)x(No. of photons).
718 ****/
719 void ScaleRdTt(InputStruct In_Parm, OutStruct * Out_Ptr)
720 {
721     short nr = In_Parm.nr;
722     short na = In_Parm.na;
723     double dr = In_Parm.dr;
724     double da = In_Parm.da;
725     short ir,ia;
726     double scale1, scale2;
727
728     scale1 = 4.0*PI*PI*dr*sin(da/2)*dr*In_Parm.num_photons;
729     /* The factor (ir+0.5)*sin(2a) to be added. */
730
731     for(ir=0; ir<nr; ir++)
732         for(ia=0; ia<na; ia++) {
733             scale2 = 1.0/((ir+0.5)*sin(2.0*(ia+0.5)*da)*scale1);
734             Out_Ptr->Rd_ra[ir][ia] *= scale2;
735             Out_Ptr->Tt_ra[ir][ia] *= scale2;
736         }
737
738     scale1 = 2.0*PI*dr*dr*In_Parm.num_photons;
739     /* area is 2*PI*[(ir+0.5)*dr]*dr.*/
740     /* ir+0.5 to be added. */
741
742     for(ir=0; ir<nr; ir++) {
743         scale2 = 1.0/((ir+0.5)*scale1);
744         Out_Ptr->Rd_r[ir] *= scale2;
745         Out_Ptr->Tt_r[ir] *= scale2;
746     }
747
748     scale1 = 2.0*PI*da*In_Parm.num_photons;
749     /* solid angle is 2*PI*sin(a)*da. sin(a) to be added. */
750

```

```

751 for(ia=0; ia<na; ia++) {
752     scale2 = 1.0/(sin((ia+0.5)*da)*scale1);
753     Out_Ptr->Rd_a[ia] *= scale2;
754     Out_Ptr->Tt_a[ia] *= scale2;
755 }
756
757 scale2 = 1.0/(double)In_Parm.num_photons;
758 Out_Ptr->Rd *= scale2;
759 Out_Ptr->Tt *= scale2;
760 }
761
762 /*****
763 * Scale absorption arrays properly.
764 *****/
765 void ScaleA(InputStruct In_Parm, OutStruct * Out_Ptr)
766 {
767     short nz = In_Parm.nz;
768     short nr = In_Parm.nr;
769     double dz = In_Parm.dz;
770     double dr = In_Parm.dr;
771     short nl = In_Parm.num_layers;
772     short iz,ir;
773     short il;
774     double scale1;
775
776     /* Scale A_rz. */
777     scale1 = 2.0*PI*dr*dr*dz*In_Parm.num_photons;
778     /* volume is 2*pi*(ir+0.5)*dr*dr*dz.*/
779     /* ir+0.5 to be added. */
780     for(iz=0; iz<nz; iz++)
781         for(ir=0; ir<nr; ir++)
782             Out_Ptr->A_rz[ir][iz] /= (ir+0.5)*scale1;
783
784     /* Scale A_z. */
785     scale1 = 1.0/(dz*In_Parm.num_photons);
786     for(iz=0; iz<nz; iz++)
787         Out_Ptr->A_z[iz] *= scale1;
788
789     /* Scale A_l. Avoid int/int. */
790     scale1 = 1.0/(double)In_Parm.num_photons;
791     for(il=0; il<=nl+1; il++)
792         Out_Ptr->A_l[il] *= scale1;
793
794     Out_Ptr->A *=scale1;
795 }
796
797 /*****
798 * Sum and scale results of current run.
799 *****/
800 void SumScaleResult(InputStruct In_Parm,
801                    OutStruct * Out_Ptr)
802 {
803     /* Get 1D & 0D results. */
804     Sum2DRd(In_Parm, Out_Ptr);
805     Sum2DA(In_Parm, Out_Ptr);
806     Sum2DTt(In_Parm, Out_Ptr);
807
808     ScaleRdTt(In_Parm, Out_Ptr);

```



```

809   ScaleA(In_Parm, Out_Ptr);
810 }
811
812 /*****
813  * Write the version number as the first string in the
814  * file.
815  * Use chars only so that they can be read as either
816  * ASCII or binary.
817  *****/
818 void WriteVersion(FILE *file, char *Version)
819 {
820     fprintf(file,
821         "%s \t# Version number of the file format.\n\n",
822         Version);
823     fprintf(file, "####\n# Data categories include: \n");
824     fprintf(file, "# InParm, RAT, \n");
825     fprintf(file, "# A_l, A_z, Rd_r, Rd_a, Tt_r, Tt_a, \n");
826     fprintf(file, "# A_rz, Rd_ra, Tt_ra \n####\n\n");
827 }
828
829 /*****
830  * Write the input parameters to the file.
831  *****/
832 void WriteInParm(FILE *file, InputStruct In_Parm)
833 {
834     short i;
835
836     fprintf(file,
837         "InParm \t\t\t# Input parameters. cm is used.\n");
838
839     fprintf(file,
840         "%s \tA\t\t# output file name, ASCII.\n",
841         In_Parm.out_fname);
842     fprintf(file,
843         "%ld \t\t\t# No. of photons\n", In_Parm.num_photons);
844
845     fprintf(file,
846         "%G\t%G\t\t# dz, dr [cm]\n", In_Parm.dz, In_Parm.dr);
847     fprintf(file, "%hd\t%hd\t%hd\t\t# No. of dz, dr, da.\n\n",
848         In_Parm.nz, In_Parm.nr, In_Parm.na);
849
850     fprintf(file,
851         "%hd\t\t\t\t\t# Number of layers\n",
852         In_Parm.num_layers);
853     fprintf(file,
854         "#n\tmua\tmus\tg\t\t# One line for each layer\n");
855     fprintf(file,
856         "%G\t\t\t\t\t# n for medium above\n",
857         In_Parm.layerspecs[0].n);
858     for(i=1; i<=In_Parm.num_layers; i++) {
859         LayerStruct s;
860         s = In_Parm.layerspecs[i];
861         fprintf(file, "%G\t%G\t%G\t%G\t%G\t\t# layer %hd\n",
862             s.n, s.mua, s.mus, s.g, s.z1-s.z0, i);
863     }
864     fprintf(file, "%G\t\t\t\t\t# n for medium below\n\n",
865         In_Parm.layerspecs[i].n);
866 }

```

```

867
868 /*****
869  * Write reflectance, absorption, transmission.
870  *****/
871 void WriteRAT(FILE * file, OutStruct Out_Parm)
872 {
873     fprintf(file,
874         "RAT #Reflectance, absorption, transmission. \n");
875     /* flag. */
876
877     fprintf(file,
878         "%-14.6G \t#Specular reflectance [-]\n", Out_Parm.Rsp);
879     fprintf(file,
880         "%-14.6G \t#Diffuse reflectance [-]\n", Out_Parm.Rd);
881     fprintf(file,
882         "%-14.6G \t#Absorbed fraction [-]\n", Out_Parm.A);
883     fprintf(file,
884         "%-14.6G \t#Transmittance [-]\n", Out_Parm.Tt);
885
886     fprintf(file, "\n");
887 }
888
889 /*****
890  * Write absorption as a function of layer.
891  *****/
892 void WriteA_layer(FILE * file,
893                 short Num_Layers,
894                 OutStruct Out_Parm)
895 {
896     short i;
897
898     fprintf(file,
899         "A_l #Absorption as a function of layer. [-]\n");
900     /* flag. */
901
902     for(i=1; i<=Num_Layers; i++)
903         fprintf(file, "%12.4G\n", Out_Parm.A_l[i]);
904     fprintf(file, "\n");
905 }
906
907 /*****
908  * 5 numbers each line.
909  *****/
910 void WriteRd_ra(FILE * file,
911                short Nr,
912                short Na,
913                OutStruct Out_Parm)
914 {
915     short ir, ia;
916
917     fprintf(file,
918         "%s\n%s\n%s\n%s\n%s\n%s\n", /* flag. */
919         "# Rd[r][angle]. [1/(cm2sr)].",
920         "# Rd[0][0], [0][1],...[0][na-1]",
921         "# Rd[1][0], [1][1],...[1][na-1]",
922         "# ...",
923         "# Rd[nr-1][0], [nr-1][1],...[nr-1][na-1]",
924         "Rd_ra");

```

```
925
926   for(ir=0;ir<Nr;ir++)
927     for(ia=0;ia<Na;ia++) {
928       fprintf(file, "%12.4E ", Out_Parm.Rd_ra[ir][ia]);
929       if( (ir*Na + ia + 1)%5 == 0) fprintf(file, "\n");
930     }
931
932   fprintf(file, "\n");
933 }
934
935 /*****
936  * 1 number each line.
937 *****/
938 void WriteRd_r(FILE * file,
939               short Nr,
940               OutStruct Out_Parm)
941 {
942   short ir;
943
944   fprintf(file,
945           "Rd_r #Rd[0], [1],..Rd[nr-1]. [1/cm2]\n"); /* flag. */
946
947   for(ir=0;ir<Nr;ir++) {
948     fprintf(file, "%12.4E\n", Out_Parm.Rd_r[ir]);
949   }
950
951   fprintf(file, "\n");
952 }
953
954 /*****
955  * 1 number each line.
956 *****/
957 void WriteRd_a(FILE * file,
958               short Na,
959               OutStruct Out_Parm)
960 {
961   short ia;
962
963   fprintf(file,
964           "Rd_a #Rd[0], [1],..Rd[na-1]. [sr-1]\n"); /* flag. */
965
966   for(ia=0;ia<Na;ia++) {
967     fprintf(file, "%12.4E\n", Out_Parm.Rd_a[ia]);
968   }
969
970   fprintf(file, "\n");
971 }
972
973 /*****
974  * 5 numbers each line.
975 *****/
976 void WriteTt_ra(FILE * file,
977                short Nr,
978                short Na,
979                OutStruct Out_Parm)
980 {
981   short ir, ia;
982
```

```

983 fprintf(file,
984     "%s\n%s\n%s\n%s\n%s\n%s\n", /* flag. */
985     "# Tt[r][angle]. [1/(cm2sr)].",
986     "# Tt[0][0], [0][1],...[0][na-1]",
987     "# Tt[1][0], [1][1],...[1][na-1]",
988     "# ...",
989     "# Tt[nr-1][0], [nr-1][1],...[nr-1][na-1]",
990     "Tt_ra");
991
992 for(ir=0;ir<Nr;ir++)
993     for(ia=0;ia<Na;ia++) {
994         fprintf(file, "%12.4E ", Out_Parm.Tt_ra[ir][ia]);
995         if( (ir*Na + ia + 1)%5 == 0) fprintf(file, "\n");
996     }
997
998 fprintf(file, "\n");
999 }
1000
1001 /*****
1002 * 5 numbers each line.
1003 *****/
1004 void WriteA_rz(FILE * file,
1005               short Nr,
1006               short Nz,
1007               OutStruct Out_Parm)
1008 {
1009     short iz, ir;
1010
1011     fprintf(file,
1012         "%s\n%s\n%s\n%s\n%s\n%s\n", /* flag. */
1013         "# A[r][z]. [1/cm3]",
1014         "# A[0][0], [0][1],...[0][nz-1]",
1015         "# A[1][0], [1][1],...[1][nz-1]",
1016         "# ...",
1017         "# A[nr-1][0], [nr-1][1],...[nr-1][nz-1]",
1018         "A_rz");
1019
1020     for(ir=0;ir<Nr;ir++)
1021         for(iz=0;iz<Nz;iz++) {
1022             fprintf(file, "%12.4E ", Out_Parm.A_rz[ir][iz]);
1023             if( (ir*Nz + iz + 1)%5 == 0) fprintf(file, "\n");
1024         }
1025
1026     fprintf(file, "\n");
1027 }
1028
1029 /*****
1030 * 1 number each line.
1031 *****/
1032 void WriteA_z(FILE * file,
1033               short Nz,
1034               OutStruct Out_Parm)
1035 {
1036     short iz;
1037
1038     fprintf(file,
1039         "A_z #A[0], [1],...A[nz-1]. [1/cm]\n"); /* flag. */
1040

```

```

1041     for(iz=0;iz<Nz;iz++) {
1042         fprintf(file, "%12.4E\n", Out_Parm.A_z[iz]);
1043     }
1044
1045     fprintf(file, "\n");
1046 }
1047
1048 /*****
1049  * 1 number each line.
1050 *****/
1051 void WriteTt_r(FILE * file,
1052              short Nr,
1053              OutStruct Out_Parm)
1054 {
1055     short ir;
1056
1057     fprintf(file,
1058            "Tt_r #Tt[0], [1],..Tt[nr-1]. [1/cm2]\n"); /* flag. */
1059
1060     for(ir=0;ir<Nr;ir++) {
1061         fprintf(file, "%12.4E\n", Out_Parm.Tt_r[ir]);
1062     }
1063
1064     fprintf(file, "\n");
1065 }
1066
1067 /*****
1068  * 1 number each line.
1069 *****/
1070 void WriteTt_a(FILE * file,
1071              short Na,
1072              OutStruct Out_Parm)
1073 {
1074     short ia;
1075
1076     fprintf(file,
1077            "Tt_a #Tt[0], [1],..Tt[na-1]. [sr-1]\n"); /* flag. */
1078
1079     for(ia=0;ia<Na;ia++) {
1080         fprintf(file, "%12.4E\n", Out_Parm.Tt_a[ia]);
1081     }
1082
1083     fprintf(file, "\n");
1084 }
1085
1086 /*****
1087 *****/
1088 void WriteResult(InputStruct In_Parm,
1089                OutStruct Out_Parm,
1090                char * TimeReport)
1091 {
1092     FILE *file;
1093
1094     file = fopen(In_Parm.out_fname, "w");
1095     if(file == NULL) nrerror("Cannot open file to write.\n");
1096
1097     if(toupper(In_Parm.out_fformat) == 'A')
1098         WriteVersion(file, "A1");

```

```
1099 else
1100     WriteVersion(file, "B1");
1101
1102 fprintf(file, "# %s", TimeReport);
1103 fprintf(file, "\n");
1104
1105 WriteInParm(file, In_Parm);
1106 WriteRAT(file, Out_Parm);
1107     /* reflectance, absorption, transmittance. */
1108
1109     /* 1D arrays. */
1110 WriteA_layer(file, In_Parm.num_layers, Out_Parm);
1111 WriteA_z(file, In_Parm.nz, Out_Parm);
1112 WriteRd_r(file, In_Parm.nr, Out_Parm);
1113 WriteRd_a(file, In_Parm.na, Out_Parm);
1114 WriteTt_r(file, In_Parm.nr, Out_Parm);
1115 WriteTt_a(file, In_Parm.na, Out_Parm);
1116
1117     /* 2D arrays. */
1118 WriteA_rz(file, In_Parm.nr, In_Parm.nz, Out_Parm);
1119 WriteRd_ra(file, In_Parm.nr, In_Parm.na, Out_Parm);
1120 WriteTt_ra(file, In_Parm.nr, In_Parm.na, Out_Parm);
1121
1122 fclose(file);
1123 }
```

**B.4 mcmlgo.c**

```

1  /*****
2  * Copyright Univ. of Texas M.D. Anderson Cancer Center
3  * 1992.
4  *
5  * Launch, move, and record photon weight.
6  *****/
7
8  #include "mcml.h"
9
10 #define STANDARDTEST 0
11 /* testing program using fixed rnd seed. */
12
13 #define PARTIALREFLECTION 0
14 /* l=split photon, 0=statistical reflection. */
15
16 #define COSZERO (1.0-1.0E-12)
17 /* cosine of about 1e-6 rad. */
18
19 #define COS90D 1.0E-6
20 /* cosine of about 1.57 - 1e-6 rad. */
21
22
23 /*****
24 * A random number generator from Numerical Recipes in C.
25 *****/
26 #define MBIG 1000000000
27 #define MSEED 161803398
28 #define MZ 0
29 #define FAC 1.0E-9
30
31 float ran3(int *idum)
32 {
33     static int inext,inextp;
34     static long ma[56];
35     static int iff=0;
36     long mj,mk;
37     int i,ii,k;
38
39     if (*idum < 0 || iff == 0) {
40         iff=1;
41         mj=MSEED-(*idum < 0 ? -*idum : *idum);
42         mj %= MBIG;
43         ma[55]=mj;
44         mk=1;
45         for (i=1;i<=54;i++) {
46             ii=(21*i) % 55;
47             ma[ii]=mk;
48             mk=mj-mk;
49             if (mk < MZ) mk += MBIG;
50             mj=ma[ii];
51         }
52         for (k=1;k<=4;k++)
53             for (i=1;i<=55;i++) {
54                 ma[i] -= ma[1+(i+30) % 55];

```

```

55     if (ma[i] < MZ) ma[i] += MBIG;
56     }
57     inext=0;
58     inextp=31;
59     *idum=1;
60     }
61     if (++inext == 56) inext=1;
62     if (++inextp == 56) inextp=1;
63     mj=ma[inext]-ma[inextp];
64     if (mj < MZ) mj += MBIG;
65     ma[inext]=mj;
66     return mj*FAC;
67 }
68
69 #undef MBIG
70 #undef MSEED
71 #undef MZ
72 #undef FAC
73
74
75 /*****
76  * Generate a random number between 0 and 1. Take a
77  * number as seed the first time entering the function.
78  * The seed is limited to 1<<15.
79  * We found that when idum is too large, ran3 may return
80  * numbers beyond 0 and 1.
81  ****/
82 double RandomNum(void)
83 {
84     static Boolean first_time=1;
85     static int idum; /* seed for ran3. */
86
87     if(first_time) {
88 #if STANDARDTEST /* Use fixed seed to test the program. */
89         idum = - 1;
90 #else
91         idum = -(int)time(NULL)%(1<<15);
92         /* use 16-bit integer as the seed. */
93 #endif
94         ran3(&idum);
95         first_time = 0;
96         idum = 1;
97     }
98
99     return( (double)ran3(&idum) );
100 }
101
102 /*****
103  * Compute the specular reflection.
104  *
105  * If the first layer is a turbid medium, use the Fresnel
106  * reflection from the boundary of the first layer as the
107  * specular reflectance.
108  *
109  * If the first layer is glass, multiple reflections in
110  * the first layer is considered to get the specular
111  * reflectance.
112  *

```



```

113 * The subroutine assumes the Layerspecs array is correctly
114 * initialized.
115 ****/
116 double Rspecular(LayerStruct * Layerspecs_Ptr)
117 {
118     double r1, r2;
119     /* direct reflections from the 1st and 2nd layers. */
120     double temp;
121
122     temp = (Layerspecs_Ptr[0].n - Layerspecs_Ptr[1].n)
123           / (Layerspecs_Ptr[0].n + Layerspecs_Ptr[1].n);
124     r1 = temp*temp;
125
126     if((Layerspecs_Ptr[1].mua == 0.0)
127     && (Layerspecs_Ptr[1].mus == 0.0)) { /* glass layer. */
128         temp = (Layerspecs_Ptr[1].n - Layerspecs_Ptr[2].n)
129               / (Layerspecs_Ptr[1].n + Layerspecs_Ptr[2].n);
130         r2 = temp*temp;
131         r1 = r1 + (1-r1)*(1-r1)*r2/(1-r1*r2);
132     }
133
134     return (r1);
135 }
136
137 /*****
138 * Initialize a photon packet.
139 *****/
140 void LaunchPhoton(double Rspecular,
141                  LayerStruct * Layerspecs_Ptr,
142                  PhotonStruct * Photon_Ptr)
143 {
144     Photon_Ptr->w      = 1.0 - Rspecular;
145     Photon_Ptr->dead   = 0;
146     Photon_Ptr->layer  = 1;
147     Photon_Ptr->s      = 0;
148     Photon_Ptr->sleft  = 0;
149
150     Photon_Ptr->x      = 0.0;
151     Photon_Ptr->y      = 0.0;
152     Photon_Ptr->z      = 0.0;
153     Photon_Ptr->ux     = 0.0;
154     Photon_Ptr->uy     = 0.0;
155     Photon_Ptr->uz     = 1.0;
156
157     if((Layerspecs_Ptr[1].mua == 0.0)
158     && (Layerspecs_Ptr[1].mus == 0.0)) { /* glass layer. */
159         Photon_Ptr->layer  = 2;
160         Photon_Ptr->z      = Layerspecs_Ptr[2].z0;
161     }
162 }
163
164 /*****
165 * Choose (sample) a new theta angle for photon propagation
166 * according to the anisotropy.
167 *
168 * If anisotropy g is 0, then
169 *     cos(theta) = 2*rand-1.
170 * otherwise

```

```

171 *      sample according to the Henyey-Greenstein function.
172 *
173 * Returns the cosine of the polar deflection angle theta.
174 ****/
175 double SpinTheta(double g)
176 {
177     double cost;
178
179     if(g == 0.0)
180         cost = 2*RandomNum() -1;
181     else {
182         double temp = (1-g*g)/(1-g+2*g*RandomNum());
183         cost = (1+g*g - temp*temp)/(2*g);
184     }
185     return(cost);
186 }
187
188
189 /*****
190 * Choose a new direction for photon propagation by
191 * sampling the polar deflection angle theta and the
192 * azimuthal angle psi.
193 *
194 * Note:
195 *     theta: 0 - pi so sin(theta) is always positive
196 *     feel free to use sqrt() for cos(theta).
197 *
198 *     psi: 0 - 2pi
199 *     for 0-pi sin(psi) is +
200 *     for pi-2pi sin(psi) is -
201 ****/
202 void Spin(double g,
203           PhotonStruct * Photon_Ptr)
204 {
205     double cost, sint;      /* cosine and sine of the */
206                             /* polar deflection angle theta. */
207     double cosp, sinp;     /* cosine and sine of the */
208                             /* azimuthal angle psi. */
209     double ux = Photon_Ptr->ux;
210     double uy = Photon_Ptr->uy;
211     double uz = Photon_Ptr->uz;
212     double psi;
213
214     cost = SpinTheta(g);
215     sint = sqrt(1.0 - cost*cost);
216     /* sqrt() is faster than sin(). */
217
218     psi = 2.0*PI*RandomNum(); /* spin psi 0-2pi. */
219     cosp = cos(psi);
220     if(psi<PI)
221         sinp = sqrt(1.0 - cosp*cosp);
222     /* sqrt() is faster than sin(). */
223     else
224         sinp = - sqrt(1.0 - cosp*cosp);
225
226     if(fabs(uz) > COSZERO) { /* normal incident. */
227         Photon_Ptr->ux = sint*cosp;
228         Photon_Ptr->uy = sint*sinp;

```

```

229     Photon_Ptr->uz = cost*SIGN(uz);
230     /* SIGN() is faster than division. */
231 }
232 else { /* regular incident. */
233     double temp = sqrt(1.0 - uz*uz);
234     Photon_Ptr->ux = sint*(ux*uz*cosp - uy*sinp)
235                 /temp + ux*cost;
236     Photon_Ptr->uy = sint*(uy*uz*cosp + ux*sinp)
237                 /temp + uy*cost;
238     Photon_Ptr->uz = -sint*cosp*temp + uz*cost;
239 }
240 }
241
242 /*****
243 * Move the photon s away in the current layer of medium.
244 *****/
245 void Hop(PhotonStruct * Photon_Ptr)
246 {
247     double s = Photon_Ptr->s;
248
249     Photon_Ptr->x += s*Photon_Ptr->ux;
250     Photon_Ptr->y += s*Photon_Ptr->uy;
251     Photon_Ptr->z += s*Photon_Ptr->uz;
252 }
253
254 /*****
255 * If uz != 0, return the photon step size in glass,
256 * Otherwise, return 0.
257 *
258 * The step size is the distance between the current
259 * position and the boundary in the photon direction.
260 *
261 * Make sure uz !=0 before calling this function.
262 *****/
263 void StepSizeInGlass(PhotonStruct * Photon_Ptr,
264                     InputStruct * In_Ptr)
265 {
266     double dl_b; /* step size to boundary. */
267     short layer = Photon_Ptr->layer;
268     double uz = Photon_Ptr->uz;
269
270     /* Stepsize to the boundary. */
271     if(uz>0.0)
272         dl_b = (In_Ptr->layerspecs[layer].z1 - Photon_Ptr->z)
273             /uz;
274     else if(uz<0.0)
275         dl_b = (In_Ptr->layerspecs[layer].z0 - Photon_Ptr->z)
276             /uz;
277     else
278         dl_b = 0.0;
279
280     Photon_Ptr->s = dl_b;
281 }
282
283 /*****
284 * Pick a step size for a photon packet when it is in
285 * tissue.
286 * If the member sleft is zero, make a new step size

```

```

287 * with: -log(rnd)/(mua+mus).
288 * Otherwise, pick up the leftover in sleft.
289 *
290 * Layer is the index to layer.
291 * In_Ptr is the input parameters.
292 ****/
293 void StepSizeInTissue(PhotonStruct * Photon_Ptr,
294                      InputStruct * In_Ptr)
295 {
296     short layer = Photon_Ptr->layer;
297     double mua = In_Ptr->layerspecs[layer].mua;
298     double mus = In_Ptr->layerspecs[layer].mus;
299
300     if(Photon_Ptr->sleft == 0.0) { /* make a new step. */
301         double rnd;
302
303         do rnd = RandomNum();
304            while( rnd <= 0.0 ); /* avoid zero. */
305         Photon_Ptr->s = -log(rnd)/(mua+mus);
306     }
307     else { /* take the leftover. */
308         Photon_Ptr->s = Photon_Ptr->sleft/(mua+mus);
309         Photon_Ptr->sleft = 0.0;
310     }
311 }
312
313 /*****
314 * Check if the step will hit the boundary.
315 * Return 1 if hit boundary.
316 * Return 0 otherwise.
317 *
318 * If the projected step hits the boundary, the members
319 * s and sleft of Photon_Ptr are updated.
320 *****/
321 Boolean HitBoundary(PhotonStruct * Photon_Ptr,
322                    InputStruct * In_Ptr)
323 {
324     double dl_b; /* length to boundary. */
325     short layer = Photon_Ptr->layer;
326     double uz = Photon_Ptr->uz;
327     Boolean hit;
328
329     /* Distance to the boundary. */
330     if(uz>0.0)
331         dl_b = (In_Ptr->layerspecs[layer].z1
332                - Photon_Ptr->z)/uz; /* dl_b>0. */
333     else if(uz<0.0)
334         dl_b = (In_Ptr->layerspecs[layer].z0
335                - Photon_Ptr->z)/uz; /* dl_b>0. */
336
337     if(uz != 0.0 && Photon_Ptr->s > dl_b) {
338         /* not horizontal & crossing. */
339         double mut = In_Ptr->layerspecs[layer].mua
340                    + In_Ptr->layerspecs[layer].mus;
341
342         Photon_Ptr->sleft = (Photon_Ptr->s - dl_b)*mut;
343         Photon_Ptr->s = dl_b;
344         hit = 1;

```

```

345 }
346 else
347     hit = 0;
348
349 return(hit);
350 }
351
352 /*****
353 * Drop photon weight inside the tissue (not glass).
354 *
355 * The photon is assumed not dead.
356 *
357 * The weight drop is dw = w*mua/(mua+mus).
358 *
359 * The dropped weight is assigned to the absorption array
360 * elements.
361 *****/
362 void Drop(InputStruct * In_Ptr,
363           PhotonStruct * Photon_Ptr,
364           OutStruct * Out_Ptr)
365 {
366     double dwa; /* absorbed weight.*/
367     double x = Photon_Ptr->x;
368     double y = Photon_Ptr->y;
369     short iz, ir; /* index to z & r. */
370     short layer = Photon_Ptr->layer;
371     double mua, mus;
372
373     /* compute array indices. */
374     iz = (short)(Photon_Ptr->z/In_Ptr->dz);
375     if(iz>In_Ptr->nz-1) iz=In_Ptr->nz-1;
376
377     ir = (short)(sqrt(x*x+y*y)/In_Ptr->dr);
378     if(ir>In_Ptr->nr-1) ir=In_Ptr->nr-1;
379
380     /* update photon weight. */
381     mua = In_Ptr->layerspecs[layer].mua;
382     mus = In_Ptr->layerspecs[layer].mus;
383     dwa = Photon_Ptr->w * mua/(mua+mus);
384     Photon_Ptr->w -= dwa;
385
386     /* assign dwa to the absorption array element. */
387     Out_Ptr->A_rz[ir][iz] += dwa;
388 }
389
390 /*****
391 * The photon weight is small, and the photon packet tries
392 * to survive a roulette.
393 *****/
394 void Roulette(PhotonStruct * Photon_Ptr)
395 {
396     if(Photon_Ptr->w == 0.0)
397         Photon_Ptr->dead = 1;
398     else if(RandomNum() < CHANCE) /* survived the roulette.*/
399         Photon_Ptr->w /= CHANCE;
400     else
401         Photon_Ptr->dead = 1;
402 }

```

```

403
404 /*****
405  * Compute the Fresnel reflectance.
406  *
407  * Make sure that the cosine of the incident angle a1
408  * is positive, and the case when the angle is greater
409  * than the critical angle is ruled out.
410  *
411  * Avoid trigonometric function operations as much as
412  * possible, because they are computation-intensive.
413  *****/
414 double RFresnel(double n1, /* incident refractive index.*/
415                 double n2, /* transmit refractive index.*/
416                 double ca1, /* cosine of the incident */
417                        /* angle. 0<a1<90 degrees. */
418                 double * ca2_Ptr) /* pointer to the */
419                        /* cosine of the transmission */
420                        /* angle. a2>0. */
421 {
422     double r;
423
424     if(n1==n2) {                /** matched boundary. **/
425         *ca2_Ptr = ca1;
426         r = 0.0;
427     }
428     else if(ca1>COSZERO) {     /** normal incident. **/
429         *ca2_Ptr = ca1;
430         r = (n2-n1)/(n2+n1);
431         r *= r;
432     }
433     else if(ca1<COS90D) {     /** very slant. **/
434         *ca2_Ptr = 0.0;
435         r = 1.0;
436     }
437     else {                    /** general. **/
438         double sa1, sa2;
439         /* sine of the incident and transmission angles. */
440         double ca2;
441
442         sa1 = sqrt(1-ca1*ca1);
443         sa2 = n1*sa1/n2;
444         if(sa2>=1.0) {
445             /* double check for total internal reflection. */
446             *ca2_Ptr = 0.0;
447             r = 1.0;
448         }
449         else {
450             double cap, cam; /* cosines of the sum ap or */
451                            /* difference am of the two */
452                            /* angles. ap = a1+a2 */
453                            /* am = a1 - a2. */
454             double sap, sam; /* sines. */
455
456             *ca2_Ptr = ca2 = sqrt(1-sa2*sa2);
457
458             cap = ca1*ca2 - sa1*sa2; /* c+ = cc - ss. */
459             cam = ca1*ca2 + sa1*sa2; /* c- = cc + ss. */
460             sap = sa1*ca2 + ca1*sa2; /* s+ = sc + cs. */

```

```

461     sam = sa1*ca2 - ca1*sa2; /* s- = sc - cs. */
462     r = 0.5*sam*sam*(cam*cam+cap*cap)/(sap*sap*cam*cam);
463     /* rearranged for speed. */
464 }
465 }
466 return(r);
467 }
468
469 /*****
470 * Record the photon weight exiting the first layer(uz<0),
471 * no matter whether the layer is glass or not, to the
472 * reflection array.
473 *
474 * Update the photon weight as well.
475 *****/
476 void RecordR(double      Refl, /* reflectance. */
477             InputStruct * In_Ptr,
478             PhotonStruct * Photon_Ptr,
479             OutStruct *   Out_Ptr)
480 {
481     double x = Photon_Ptr->x;
482     double y = Photon_Ptr->y;
483     short  ir, ia; /* index to r & angle. */
484
485     ir = (short)(sqrt(x*x+y*y)/In_Ptr->dr);
486     if(ir>In_Ptr->nr-1) ir=In_Ptr->nr-1;
487
488     ia = (short)(acos(-Photon_Ptr->uz)/In_Ptr->da);
489     if(ia>In_Ptr->na-1) ia=In_Ptr->na-1;
490
491     /* assign photon to the reflection array element. */
492     Out_Ptr->Rd_ra[ir][ia] += Photon_Ptr->w*(1.0-Refl);
493
494     Photon_Ptr->w *= Refl;
495 }
496
497 /*****
498 * Record the photon weight exiting the last layer(uz>0),
499 * no matter whether the layer is glass or not, to the
500 * transmittance array.
501 *
502 * Update the photon weight as well.
503 *****/
504 void RecordT(double      Refl,
505             InputStruct * In_Ptr,
506             PhotonStruct * Photon_Ptr,
507             OutStruct *   Out_Ptr)
508 {
509     double x = Photon_Ptr->x;
510     double y = Photon_Ptr->y;
511     short  ir, ia; /* index to r & angle. */
512
513     ir = (short)(sqrt(x*x+y*y)/In_Ptr->dr);
514     if(ir>In_Ptr->nr-1) ir=In_Ptr->nr-1;
515
516     ia = (short)(acos(Photon_Ptr->uz)/In_Ptr->da);
517     if(ia>In_Ptr->na-1) ia=In_Ptr->na-1;
518

```

```

519  /* assign photon to the transmittance array element. */
520  Out_Ptr->Tt_ra[ir][ia] += Photon_Ptr->w*(1.0-Refl);
521
522  Photon_Ptr->w *= Refl;
523 }
524
525 /*****
526  * Decide whether the photon will be transmitted or
527  * reflected on the upper boundary (uz<0) of the current
528  * layer.
529  *
530  * If "layer" is the first layer, the photon packet will
531  * be partially transmitted and partially reflected if
532  * PARTIALREFLECTION is set to 1,
533  * or the photon packet will be either transmitted or
534  * reflected determined statistically if PARTIALREFLECTION
535  * is set to 0.
536  *
537  * Record the transmitted photon weight as reflection.
538  *
539  * If the "layer" is not the first layer and the photon
540  * packet is transmitted, move the photon to "layer-1".
541  *
542  * Update the photon parameters.
543  *****/
544 void CrossUpOrNot(InputStruct *   In_Ptr,
545                  PhotonStruct * Photon_Ptr,
546                  OutStruct *    Out_Ptr)
547 {
548   double uz = Photon_Ptr->uz; /* z directional cosine. */
549   double uz1; /* cosines of transmission alpha. always */
550              /* positive. */
551   double r=0.0; /* reflectance */
552   short layer = Photon_Ptr->layer;
553   double ni = In_Ptr->layerspecs[layer].n;
554   double nt = In_Ptr->layerspecs[layer-1].n;
555
556   /* Get r. */
557   if( - uz <= In_Ptr->layerspecs[layer].cos_crit0)
558     r=1.0; /* total internal reflection. */
559   else r = RFresnel(ni, nt, -uz, &uz1);
560
561   #if PARTIALREFLECTION
562   if(layer == 1 && r<1.0) { /* partially transmitted. */
563     Photon_Ptr->uz = -uz1; /* transmitted photon. */
564     RecordR(r, In_Ptr, Photon_Ptr, Out_Ptr);
565     Photon_Ptr->uz = -uz; /* reflected photon. */
566   }
567   else if(RandomNum() > r) { /* transmitted to layer-1. */
568     Photon_Ptr->layer--;
569     Photon_Ptr->ux *= ni/nt;
570     Photon_Ptr->uy *= ni/nt;
571     Photon_Ptr->uz = -uz1;
572   }
573   else /* reflected. */
574     Photon_Ptr->uz = -uz;
575   #else
576   if(RandomNum() > r) { /* transmitted to layer-1. */

```



```

577     if(layer==1) {
578         Photon_Ptr->uz = -uz1;
579         RecordR(0.0, In_Ptr, Photon_Ptr, Out_Ptr);
580         Photon_Ptr->dead = 1;
581     }
582     else {
583         Photon_Ptr->layer--;
584         Photon_Ptr->ux *= ni/nt;
585         Photon_Ptr->uy *= ni/nt;
586         Photon_Ptr->uz = -uz1;
587     }
588 }
589 else /* reflected. */
590     Photon_Ptr->uz = -uz;
591 #endif
592 }
593
594 /*****
595 * Decide whether the photon will be transmitted or be
596 * reflected on the bottom boundary (uz>0) of the current
597 * layer.
598 *
599 * If the photon is transmitted, move the photon to
600 * "layer+1". If "layer" is the last layer, record the
601 * transmitted weight as transmittance. See comments for
602 * CrossUpOrNot.
603 *
604 * Update the photon parameters.
605 *****/
606 void CrossDnOrNot(InputStruct * In_Ptr,
607                  PhotonStruct * Photon_Ptr,
608                  OutStruct * Out_Ptr)
609 {
610     double uz = Photon_Ptr->uz; /* z directional cosine. */
611     double uz1; /* cosines of transmission alpha. */
612     double r=0.0; /* reflectance */
613     short layer = Photon_Ptr->layer;
614     double ni = In_Ptr->layerspecs[layer].n;
615     double nt = In_Ptr->layerspecs[layer+1].n;
616
617     /* Get r. */
618     if( uz <= In_Ptr->layerspecs[layer].cos_crit1)
619         r=1.0; /*total internal reflection. */
620     else r = RFresnel(ni, nt, uz, &uz1);
621
622     #if PARTIALREFLECTION
623     if(layer == In_Ptr->num_layers && r<1.0) {
624         Photon_Ptr->uz = uz1;
625         RecordT(r, In_Ptr, Photon_Ptr, Out_Ptr);
626         Photon_Ptr->uz = -uz;
627     }
628     else if(RandomNum() > r) { /* transmitted to layer+1. */
629         Photon_Ptr->layer++;
630         Photon_Ptr->ux *= ni/nt;
631         Photon_Ptr->uy *= ni/nt;
632         Photon_Ptr->uz = uz1;
633     }
634     else /* reflected. */

```

```

635     Photon_Ptr->uz = -uz;
636 #else
637     if(RandomNum() > r) { /* transmitted to layer+1. */
638         if(layer == In_Ptr->num_layers) {
639             Photon_Ptr->uz = uz1;
640             RecordT(0.0, In_Ptr, Photon_Ptr, Out_Ptr);
641             Photon_Ptr->dead = 1;
642         }
643         else {
644             Photon_Ptr->layer++;
645             Photon_Ptr->ux *= ni/nt;
646             Photon_Ptr->uy *= ni/nt;
647             Photon_Ptr->uz = uz1;
648         }
649     }
650     else /* reflected. */
651         Photon_Ptr->uz = -uz;
652 #endif
653 }
654
655 /*****
656 *****/
657 void CrossOrNot(InputStruct * In_Ptr,
658                PhotonStruct * Photon_Ptr,
659                OutStruct * Out_Ptr)
660 {
661     if(Photon_Ptr->uz < 0.0)
662         CrossUpOrNot(In_Ptr, Photon_Ptr, Out_Ptr);
663     else
664         CrossDnOrNot(In_Ptr, Photon_Ptr, Out_Ptr);
665 }
666
667 /*****
668 * Move the photon packet in glass layer.
669 * Horizontal photons are killed because they will
670 * never interact with tissue again.
671 *****/
672 void HopInGlass(InputStruct * In_Ptr,
673                PhotonStruct * Photon_Ptr,
674                OutStruct * Out_Ptr)
675 {
676     double dl; /* step size. 1/cm */
677
678     if(Photon_Ptr->uz == 0.0) {
679         /* horizontal photon in glass is killed. */
680         Photon_Ptr->dead = 1;
681     }
682     else {
683         StepSizeInGlass(Photon_Ptr, In_Ptr);
684         Hop(Photon_Ptr);
685         CrossOrNot(In_Ptr, Photon_Ptr, Out_Ptr);
686     }
687 }
688
689 /*****
690 * Set a step size, move the photon, drop some weight,
691 * choose a new photon direction for propagation.
692 *

```

```

693 * When a step size is long enough for the photon to
694 * hit an interface, this step is divided into two steps.
695 * First, move the photon to the boundary free of
696 * absorption or scattering, then decide whether the
697 * photon is reflected or transmitted.
698 * Then move the photon in the current or transmission
699 * medium with the unfinished stepsize to interaction
700 * site. If the unfinished stepsize is still too long,
701 * repeat the above process.
702 *****/
703 void HopDropSpinInTissue(InputStruct * In_Ptr,
704                        PhotonStruct * Photon_Ptr,
705                        OutStruct * Out_Ptr)
706 {
707     StepSizeInTissue(Photon_Ptr, In_Ptr);
708
709     if(HitBoundary(Photon_Ptr, In_Ptr)) {
710         Hop(Photon_Ptr); /* move to boundary plane. */
711         CrossOrNot(In_Ptr, Photon_Ptr, Out_Ptr);
712     }
713     else {
714         Hop(Photon_Ptr);
715         Drop(In_Ptr, Photon_Ptr, Out_Ptr);
716         Spin(In_Ptr->layerspecs[Photon_Ptr->layer].g,
717             Photon_Ptr);
718     }
719 }
720
721 /*****
722 *****/
723 void HopDropSpin(InputStruct * In_Ptr,
724                PhotonStruct * Photon_Ptr,
725                OutStruct * Out_Ptr)
726 {
727     short layer = Photon_Ptr->layer;
728
729     if((In_Ptr->layerspecs[layer].mua == 0.0)
730     && (In_Ptr->layerspecs[layer].mus == 0.0))
731         /* glass layer. */
732         HopInGlass(In_Ptr, Photon_Ptr, Out_Ptr);
733     else
734         HopDropSpinInTissue(In_Ptr, Photon_Ptr, Out_Ptr);
735
736     if( Photon_Ptr->w < In_Ptr->Wth && !Photon_Ptr->dead)
737         Roulette(Photon_Ptr);
738 }

```

**B.5 mcmlnr.c**

```

1  /*****
2  * Copyright Univ. of Texas M.D. Anderson Cancer Center
3  * 1992.
4  *
5  * Some routines modified from Numerical Recipes in C,
6  * including error report, array or matrix declaration
7  * and releasing.
8  *****/
9  #include <stdlib.h>
10 #include <stdio.h>
11 #include <math.h>
12
13 /*****
14 * Report error message to stderr, then exit the program
15 * with signal 1.
16 *****/
17 void nrerror(char error_text[])
18 {
19 {
20     fprintf(stderr,"%s\n",error_text);
21     fprintf(stderr,"...now exiting to system...\n");
22     exit(1);
23 }
24
25 /*****
26 * Allocate an array with index from nl to nh inclusive.
27 *
28 * Original matrix and vector from Numerical Recipes in C
29 * don't initialize the elements to zero. This will
30 * be accomplished by the following functions.
31 *****/
32 double *AllocVector(short nl, short nh)
33 {
34     double *v;
35     short i;
36
37     v=(double *)malloc((unsigned) (nh-nl+1)*sizeof(double));
38     if (!v) nrerror("allocation failure in vector()");
39
40     v -= nl;
41     for(i=nl;i<=nh;i++) v[i] = 0.0; /* init. */
42     return v;
43 }
44
45 /*****
46 * Allocate a matrix with row index from nrl to nrh
47 * inclusive, and column index from ncl to nch
48 * inclusive.
49 *****/
50 double **AllocMatrix(short nrl,short nrh,
51                      short ncl,short nch)
52 {
53     short i,j;
54     double **m;

```

```
55
56 m=(double **) malloc((unsigned) (nrh-nrl+1)
57                      *sizeof(double*));
58 if (!m) nrerror("allocation failure 1 in matrix()");
59 m -= nrl;
60
61 for(i=nrl;i<=nrh;i++) {
62     m[i]=(double *) malloc((unsigned) (nch-ncl+1)
63                            *sizeof(double));
64     if (!m[i]) nrerror("allocation failure 2 in matrix()");
65     m[i] -= ncl;
66 }
67
68 for(i=nrl;i<=nrh;i++)
69     for(j=ncl;j<=nch;j++) m[i][j] = 0.0;
70 return m;
71 }
72
73 /*****
74 * Release the memory.
75 *****/
76 void FreeVector(double *v,short nl,short nh)
77 {
78     free((char*) (v+nl));
79 }
80
81 /*****
82 * Release the memory.
83 *****/
84 void FreeMatrix(double **m,short nrl,short nrh,
85                short ncl,short nch)
86 {
87     short i;
88
89     for(i=nrh;i>=nrl;i--) free((char*) (m[i]+ncl));
90     free((char*) (m+nrl));
91 }
```

## Appendix C. Makefile for the Program mcml

We present the make file used for compiling and linking the code for UNIX users. This make file (named makefile) can be placed under the same directory as the source code, and used by the UNIX command make.

```
CFLAGS =
CC=cc
RM=/bin/rm -rf
LOCAL_LIBRARIES= -lm
OBJS = mcmlmain.o mcmlgo.o mcmlio.o mcmlnr.o

.c.o:
    $(RM) $@
    $(CC) -c $(CFLAGS) $*.c
#####

all : mcml

mcml: $(OBJS)
    $(RM) $@
    $(CC) -o $@ $(OBJS) $(LOCAL_LIBRARIES)

clean::
    $(RM) mcml
    $(RM) mcmlmain.o
```

If you use ANSI Standard C compiler (acc) on SPARCstation 2, you need to change cc to acc in the second line. Similarly, if you want to use GNU C compiler, you need to use gcc instead of cc. If you need to use a debugger (e.g., dbx), you need to add the option -g to CFLAGS in the first line, and recompile the source codes using the new make file. Then, you can call the debugger (e.g., dbx mcml). To compile and link use the makefile, use:

```
make
```



**Appendix E. A Sample Output Data File of mcml**

This is a sample output data file. To limit the length of the file, we used very small numbers of grid elements as can be seen in the section of the input parameter in the file.

```

A1      # Version number of the file format.

####
# Data categories include:
# InParm, RAT,
# A_l, A_z, Rd_r, Rd_a, Tt_r, Tt_a,
# A_rz, Rd_ra, Tt_ra
####

# User time:      0.42 sec =      0.00 hr.   Simulation time of this run.

InParm          # Input parameters. cm is used.
sample.mco      A          # output file name, ASCII.
100             # No. of photons
0.1    0.1      # dz, dr [cm]
3      3        4    # No. of dz, dr, da.

2              # Number of layers
#n    mua    mus    g    d    # One line for each layer
1          # n for medium above
1.3    5     100   0.7   0.1  # layer 1
1.4    2     10    0     0.2  # layer 2
1          # n for medium below

RAT #Reflectance, absorption, transmission.
0.0170132      #Specular reflectance [-]
0.259251       #Diffuse reflectance [-]
0.708072       #Absorbed fraction [-]
0.0156549      #Transmittance [-]

A_l #Absorption as a function of layer. [-]
    0.6418
    0.06624

A_z #A[0], [1],...A[nz-1]. [1/cm]
    6.4184E+00
    4.2203E-01
    2.4034E-01

Rd_r #Rd[0], [1],...Rd[nr-1]. [1/cm2]
    7.1961E+00
    3.1968E-01
    1.9419E-02

Rd_a #Rd[0], [1],...Rd[na-1]. [sr-1]
    5.5689E-02
    6.2845E-02
    3.6396E-02
    2.9598E-02

Tt_r #Tt[0], [1],...Tt[nr-1]. [1/cm2]

```



```

1.5008E-01
4.8650E-02
4.0457E-02

Tt_a #Tt[0], [1],...Tt[na-1]. [sr-1]
1.0965E-03
3.5961E-03
3.1196E-03
1.5692E-03

# A[r][z]. [1/cm3]
# A[0][0], [0][1],...[0][nz-1]
# A[1][0], [1][1],...[1][nz-1]
# ...
# A[nr-1][0], [nr-1][1],...[nr-1][nz-1]
A_rz
1.7934E+02  5.9590E+00  2.9838E+00  7.4003E+00  1.3974E+00
7.6865E-01  5.5296E-01  6.5647E-01  4.7210E-01

# Rd[r][angle]. [1/(cm2sr)].
# Rd[0][0], [0][1],...[0][na-1]
# Rd[1][0], [1][1],...[1][na-1]
# ...
# Rd[nr-1][0], [nr-1][1],...[nr-1][na-1]
Rd_ra
1.7856E+00  2.0312E+00  1.8606E+00  4.0608E+00  0.0000E+00
1.0438E-01  7.3502E-02  2.4768E-01  4.3564E-03  1.2307E-02
8.2665E-04  5.0690E-03

# Tt[r][angle]. [1/(cm2sr)].
# Tt[0][0], [0][1],...[0][na-1]
# Tt[1][0], [1][1],...[1][na-1]
# ...
# Tt[nr-1][0], [nr-1][1],...[nr-1][na-1]
Tt_ra
0.0000E+00  2.6871E-02  0.0000E+00  2.5301E-01  0.0000E+00
9.0115E-05  4.2593E-02  0.0000E+00  7.1173E-03  2.2105E-02
1.0191E-02  6.0383E-04

```

## Appendix F. Several C Shell Scripts

### F.1 conv.bat for batch processing conv

The C Shell script "conv.bat" is used to batch process the program conv (see Section 9.4 for description of use of conv.bat).

```
# Shell script for the convolution program "conv"
# Feb. 2, 1992
#
# Format: conv.bat filename(s) output_type
# output_type includes: Rr, Ra, Az ...

# Check parm, echo the help if something is wrong.
if ($#argv == 0 || $#argv >= 3) then
  echo 'Usage: conv.bat "input_filename(s)" output_type'
  echo "output_type includes: "
  echo "I, 3, K"
  echo "Al, Az, Arz"
  echo "Rr, Ra, Rra"
  echo "Tr, Ta, Tra"
  exit
endif

# Check the second parameter.
if (! ($2 =~ [Ii3Kk] || \
  $2 =~ [Aa][LlZz] || \
  $2 =~ [Aa][Rr][Zz] || \
  $2 =~ [RrTt][RrAa] || \
  $2 =~ [RrTt][Rr][Aa])) then
  echo "Wrong parm -- $2"
  echo "output_type includes: "
  echo "I, 3, K"
  echo "Al, Az, Arz"
  echo "Rr, Ra, Rra"
  echo "Tr, Ta, Tra"
  exit(3)
endif

foreach infile ($1)
  # make sure the file is existent and readable.
  if (! -e $infile) then
    echo "File $infile not exist"
    exit(2);
  else if (! -r $infile) then
    echo "File $infile not readable"
    exit(2)
  endif

  # remove the existent output files, if any.
  if ( -e $infile:r.$2) then
    rm $infile:r.$2
  endif
endfor
```

```

# echo the command sequence to conv.
(echo i;echo $infile;\
 echo oo;echo $2;echo $infile:r.$2;echo q;echo q;echo y)\
 |conv>/dev/null

end # of foreach

```

## **F.2 p1 for pasting files of 1D arrays**

The C Shell script `p1` is used to paste side by side multiple files of 1D arrays, which are in 2 columns. If the files of 1D arrays share the same first column, `p1` will not duplicate the first column in the pasted file. If the output file is existent, then it is backed up as the original filename appended with ".bak". The original output file is still kept as part of the new output file. This script is particularly useful to prepare the data for processing and presentation by some commercial plotting softwares such as KaleidaGraph. For example, if you have three `mcml` output files `file1.Rr`, `file2.Rr`, and `file3.Rr` saved in 2 columns representing the diffuse reflectance as a function of radius  $r$ . You can combine these three files into one file by:

```
p1 "file?.Rr" filex.Rrs
```

where `filex.Rrs` is the filename of the output.

```

# Paste 1D files (in 2 columns) together side by side.
# February 7, 1992.

# Check number of arguments.
if ($#argv != 2) then
  echo 'Usage: p1 "input_file(s)" output_fname'
  exit(1)
endif

onintr catch          # Prepare to catch interrpts.

set com = $0
set infiles = $1:q
set outfile = $2

# Check validity of arguments for outfile.
if ( -e $outfile) then
  if (! -w $outfile) then
    echo $outfile not writable
    exit(2)
  endif

  cp $outfile $outfile.bak # Backup existent files.
endif

```

```
# Setup temp files with the PID number.
set outbuf = /tmp/$com:t.$$outbuf
set buf1 = /tmp/$com:t.$$buf1
set buf2 = /tmp/$com:t.$$buf2
set cmp1 = /tmp/$com:t.$$cmp1
set cmp2 = /tmp/$com:t.$$cmp2

# Run through each file, keep the results in $outbuf.
foreach infile ($infile)
  if (! -r $infile) then
    echo $infile not readable
    exit(3)
  endif

  # Delimit by tab.
  awk -F" " '{print $1 "\t" $2}' $infile >! $buf1

  if (! -e $outbuf) then
    cut -f1 $buf1 >! $cmp1
    cp $buf1 $outbuf
  else
    cut -f1 $buf1 >! $cmp2
    diff $cmp1 $cmp2 > /dev/null

    if ($status) then
      # 1st rows are not the same. Paste both columns.
      paste $outbuf $buf1 >! $buf2; cp $buf2 $outbuf
      cut -f1 $buf1 >! $cmp1
    else
      # 1st rows are the same. Paste only the 2nd column.
      cut -f2 $buf1 >! $buf2
      paste $outbuf $buf2 >! $buf1; cp $buf1 $outbuf
    endif
  endif
end

end

# Copy $outbuf to $outfile
if (! -e $outfile) then
  cp $outbuf $outfile
else
  paste $outfile $outbuf >! $buf1; cp $buf1 $outfile
endif

catch:          # jump to here if interrupted
rm -f $outbuf  $buf1 $buf2 $cmp1 $cmp2
exit(1)
```

## **Appendix G. Where to Get the Programs mcml and conv**

We will eventually set up a bulletin board of our own so that you can download the software over the network. For now, you can contact Lihong Wang, or Steven L. Jacques using the following information to get the software.

Lihong Wang, Ph. D.

Optical Imaging Laboratory, Biomedical Engineering Program

Texas A&M University, College Station, TX 77843-3120

Email: LWang@tamu.edu

URL: <http://biomed.tamu.edu/~lw>

Steven L. Jacques, Ph. D.

Oregon Medical Laser Center, Providence t. Vincent Hospital

9205 SW Barnes Rd., Portland, OR 97225

Email: [sjacques@ece.ogi.edu](mailto:sjacques@ece.ogi.edu)

URL: <http://ece.ogi.edu/omlc>

Make sure that you tell us the specific machines (including brand and model) you will use for the simulation, so that we can compile the code correctly for you. If you use IBM PC compatibles, please also tell us whether you use a math co-processor or not.

## Appendix H. Future Developments of the Package

The release is by no means the end of the package. We plan to make at least the following improvements. As we gather comments from users, we may consider even more improvements.

### Collimated responses in mcml

In this version (version 1.0) of mcml, the first photon interactions in the media are scored into the first grid elements in the r direction together with the later interactions. The first interactions are all on the z-axis, and should yield a delta function of r (Gardner *et al.*, 1992b) to be exact. Therefore, they should be scored separately as demonstrated by Gardner *et al.*

The specular reflectance is computed analytically using Fresnel's formulas. However, the reflected photons that are uninteracted inside the tissue are scored into the first grid elements in the r direction of the diffuse reflectance. To be strict, these photons should contribute to the specular reflectance rather than the diffuse reflectance although this is small in thick tissues.

The transmittance in version 1.0 of mcml does not differentiate between diffuse transmittance and unscattered transmittance. This problem and the problem with the reflectance can be solved by keeping track of the number of interactions.

### Best points for each grid element

As we have discussed in Section 4.3, we should use:

$$r_b = \left[ (n + 0.5) + \frac{1}{12(n + 0.5)} \right] \Delta r$$

instead of the center of the grid element as the coordinate of the simulated data in the nth grid element in the r direction. In the case when the radius of a Gaussian beam is comparable with the grid separation  $\Delta r$ , this may make a considerably large difference in the convolution program conv.

### Flexible photon sources

In version 1.0 of mcml, only collimated photon beams incident on the tissue surface are supported. Several other cylindrically symmetric sources should be able to be incorporated without substantially modifying the program.

The convolution program conv 1.0 only supports Gaussian beams and circularly flat beams, it can be easily adopted to convolve over arbitrary beam profiles that are cylindrically symmetric. For beams that are not cylindrically symmetric, the convolution still can be done but with longer integration time.

### Faster sampling procedures

The sampling of the step size involves an exponential computation which is computation intensive. Faster approaches can be used as discussed in Section 3.2.

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## Index

### —A—

A, 35

absorption, 4

absorption, 14, 22, 35

absorption coefficient, 33

absorption coefficient, 4, 5, 23, 90

absorption-only, 28

angularly resolved diffuse reflectance and  
transmittance, 46

anisotropy, 14

anisotropy, 4

anisotropy factor, 33

ANSI C, 85

ANSI Standard C, 85, 89

ANSI Standard C, 30

Apple Edit, 89

arrows, 13

ASCII format, 90

AXUM, 94

azimuthal angle, 14

A\_l, 35, 93

A\_rz, 35, 93

A\_z, 35, 93

### —B—

background job, 93

background processes, 93

batch process, 94

Bessel function, 69, 74

binary files, 89

binary tree, 72

binary tree, 75

bit bucket, 93

Boolean, 33

bugs, 95

buried isotropic photon sources, 109

### —C—

Cartesian coordinate system, 4

cell, the last, 20

cflow, 39

CHANCE, 31

comment lines, 89, 93

compress, 88

computation results, 45

computation time, 50

constants, 31

contour, 64, 81

conv, 78

convolution, 65

convolution, 65

convolution error, 83

convolve, 94

coordinate systems, 4

COS90D, 31

COSZERO, 31

cos\_crit0, 33

cos\_crit1, 33

critical angles, 33

cross the boundary, 36

cumulative distribution function, 7

cylindrical coordinate system, 5

### —D—

da, 34

Data structures, 32  
 dead, 32  
 deflection angle, 14  
 delta function, 28  
 depth resolved internal fluence, 48  
 diffuse reflectance, 20, 35  
 diffuse reflectances, 61, 79, 82  
 diffuse transmittance, 46  
 diffuse transmittance, 18  
 dimensional step size, 13  
 dimensionless step size, 13  
 directional cosines, 16  
 directional cosines, 10, 32  
 divergence, 69  
 dr, 34  
 duplicated filenames, 41  
 dynamic allocation, 35  
 dz, 34

—E—

editor, 89  
 eject, 86  
 electronic mail, 87  
 EMACS, 89  
 empirical formulas, 53, 56  
 empirical formulas, 60  
 Ethernet, 95  
 execution, 91  
 extended trapezoidal integration, 29  
 extended trapezoidal integration, 72  
 extraction, subset, 94  
 extrapolations, 74

—F—

file expansion, 95  
 file format, 90

file of input data, 89  
 file of output data, 93  
 File version, 90  
 filename for data output, 34  
 first photon interactions, 28  
 flat beam, 67  
 flat beams, 70  
 flow graph, 39  
 flow of the program, 30  
 flowchart, 36  
 fluences, 63, 80, 83  
 folder, 94  
 folder, 92  
 free path, 11  
 Fresnel reflectances, 11  
 Fresnel's formulas, 17  
 FTP, 89, 95

—G—

g, 33  
 Gaussian beam, 67  
 glass, 10  
 glass layer, 13, 36  
 GNUCC, 31  
 grid line separations, 90  
 grid system, 5

—H—

Henyey and Greenstein, 14  
 hybrid model, 53

—I—

IBM PC compatibles, 92  
 implicit photon capture, 10  
 impulse response, 65  
 impulse response, 64

index range of the array, 36  
input data file, 89, 95  
input parameters, 34, 93, 95  
InputStruct, 34  
instructions, 89  
integers, 95  
integral limits, 75, 77  
integrand evaluation, 74, 76  
intensity profile, 66  
interaction coefficient, 4, 11, 38  
interpolations, 73  
invariance, 65  
isotropic photon sources, 109  
isotropic photon sources, buried, 109

### —J—

job, background, 93

### —K—

KaleidaGraph, 164  
KaleidaGraph, 94  
Kermit, 89, 95

### —L—

last cells, 20  
Launch photon, 36  
layer, 32  
Layer parameter, 91  
layerspecs, 34  
LayerStruct, 33  
linear and invariant, 65  
linear approximations, 25  
linear linked list, 41  
linearity, 65  
logarithmic operation, 43  
log-log plot, 53

log-log scale, 53  
long int, 34

### —M—

Macintosh, 92  
mail, 88  
mails, 87  
make file, 30  
matched boundaries, 51  
matched boundary, 45  
Max, 76, 77  
Max, 70  
Mean free path, 2, 91  
mean free path, 12  
mean free path, transport, 49, 110  
memory, ii, 35, 41, 91  
memory, release, 41  
Microsoft Word, 89  
Min, 76, 77  
mismatched boundaries, 56  
mismatched boundary, 46  
mismatched boundary, 10  
MockWrite, 89  
modem, 95  
modified Bessel function, 69  
modify the program, 109  
Monte Carlo, 1  
mua, 33  
multi-layered tissue, 4  
multi-layered tissues, 60  
multiple runs, 91  
multiple simulations, 41  
mus, 33

### —N—

n, 33

na, 34  
 nesting depth, 39  
 network, 89  
 Norton editor, 89  
 nr, 34  
 Number of grid elements, 91  
 Number of layers, 91  
 number of photon packets, 34, 90  
 Number of runs, 90  
 numerical computation, 71  
 num\_layers, 34  
 num\_photons, 34  
 nz, 34

—O—

observation point, 66  
 operating system, 89  
 output data files, 93  
 Output filename, 90  
 OutStruct, 35  
 out\_fformat, 34  
 out\_fname, 34  
 overflow, 75  
 overflow, 20

—P—

partial reflection approach, 18  
 PARTIALREFLECTION, 31  
 path, search, 92  
 photon absorption, 14  
 photon fluence, 23  
 photon packet, 10, 32  
 photon propagation, 10  
 photon scattering, 14  
 photon termination, 19  
 PhotonStruct, 32

physical quantities, 4, 20  
 position of the photon packet, 13  
 probability density function, 7  
 probability of interaction, 11  
 process, background, 93  
 profiler, 42, 44  
 pseudo-random number generator, 7

—R—

radially resolved diffuse reflectance, 47  
 random variable, 7  
 RAT, 93  
 Rd, 35  
 Rd\_a, 35, 93  
 Rd\_r, 35, 93  
 Rd\_ra, 34, 93  
 real time, 41  
 reflectance, 17  
 reflection at boundary, 16  
 reflection at interface, 18  
 refractive index, 33  
 Refractive index, 91  
 release the memory, and continues execution, 41  
 resolution, 90  
 roulette, 34  
 roulette, 19, 39  
 Rsp, 34

—S—

s, 32  
 sampling random variables, 7  
 scattering coefficient, 33  
 scattering coefficient, 4, 5, 90  
 scattering function ), 14  
 script file, 94  
 search path, 92

- 
- search path, 86
  - semi-infinite turbid medium, 45
  - shell programming, 94
  - short, 33
  - similarity relations, 48, 110
  - sleft, 32
  - Snell's law, 17
  - software installation, 85
  - solid angle, 21, 46
  - source, 66
  - source code, 30
  - source or error, 77
  - source point, 66
  - space lines, 89, 93
  - specular reflectance, 35, 93
  - specular reflectance, 10, 20
  - spherical coordinate system, 5
  - standard errors, 45
  - STANDARDTEST, 31
  - step size, 11, 33
  - STRLEN, 31
  - subset extraction, 94
  - subset of the output data, 94
- T—**
- tar, 88
  - Taylor series, 26
  - template file, 89
  - termination, 19
  - text editors, 89
  - text format, 89
  - THINKCProfiler, 31
  - threshold weight, 34
  - time of computation, 50
  - timer, 95
  - time-shared system, 51
  - timing profile, 42, 43
  - tissue/tissue interface, 18
  - total absorption, 93
  - total diffuse reflectance, 93
  - total diffuse reflectance, 35, 45, 46
  - total diffuse reflectance and transmittance, 21
  - total diffuse transmittance, 46
  - total transmittance, 93
  - total transmittance, 45
  - trajectory, 2
  - transformation of variables, 67
  - transmission at boundary, 16
  - transmission at interface, 18
  - transmittance, 17
  - transmittance, 20
  - transmittances, 61
  - transmittances, 79, 82
  - transport mean free path, 49
  - transport mean free path, 110
  - trapezoidal rule, 71
  - Tt, 35
  - Tt\_a, 35, 93
  - Tt\_r, 35, 93
  - Tt\_ra, 35
  - Tt\_ra, 93
- U—**
- uncompress, 87
  - unit of length, 5
  - UNIX, 92
  - unscattered transmittance, 18
  - unscattered transmittance, 46
  - user time, 41, 93, 95
  - user times, 50
  - uudecode, 87
  - uuencode, 88

---

ux, 32

uy, 32

uz, 32

—V—

variance, 90

variance reduction technique, 10

vi, 89

—W—

w, 32

wave phenomenon, 1

weight, 10

wild cards, 94

Word, 89

Wth, 34

—X—

x, 32

—Y—

y, 32

—Z—

z, 32

z0, 33

z1, 33