Simulation of distribution of radiation energy density in water balls

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Abstract The distribution of energy deposition density in radiate region and its surrounding areas from γ-rays was simulated and analyzed for a water-ball model with Geant4 package（Geant4.7.0,2005） developed by CERN (the Center of European Research of Nucleus). The results show that the distribution depends strongly on the collimating condition of radiation beam. A well-collimated beam would reduce radiation effects on surrounding areas.

Key words Water ball, Radiation energy density distribution, Energy deposition, Geant 4

CLC numbers TN25, O571.33

1 Introduction

In this work, we have carried out a numerical simulation on energy deposition from γ-rays generated by ^{60}Co sources under different collimating conditions and hope to shed light on how to optimize the size of a radiation beam and its collimation.

Fig.1 illustrates a typical situation, where region *A* (malignant tissue) represents the area that need to be radiated, region *B* represents the immediate surroundings of region *A*. The radiation passes through region *B* before entering region *A* and it penetrates through region *B*. In addition, the interaction of the radiation with atoms and molecules in region *A* could generate secondary radiation effect in region *B*. In order to minimize the radiation effect on region *B*, a number of factors need to be considered and adjusted.

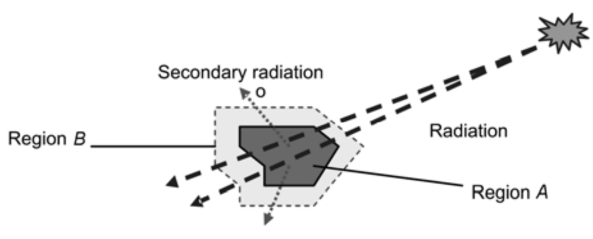

Fig.1 Effect of radiation on tissue.

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2 Computer simulation

We have used a Monte Carlo program, Geant 4, which is a toolkit designed initially for simulating nuclear and high energy physics experiments, but in recent years has been applied in a wide range of subjects including radiation analysis, space and cosmic ray analysis and, more recently, medical oncology analysis and evaluations.[1] The toolkit is based on the object oriented technology. It provides transparency for implementation of various physics parameters.

A set of models that describes the interaction of photons and electrons with matters at low energies has been implemented in the toolkit. The physical processes involved include photoelectric effect, Compton scattering, Raleigh effect, Bremsstrahlung and ionization.[2] A low energy limit for particle interaction corresponding to the minimal energy within the validity range of the models is denied. A higher threshold for any specific application can be alternatively defined by user.[3]

Geant 4 is supported under various operating systems. In our simulation, we used the one under Linux (Redhat8). The simulation was run on dedicated Pentium-IV personal computers.

3 Simulation method

The radiation source used in the simulation is ^{60}Co which emits γ-rays with two different energies at 1.333 and 1.173 MeV.[4] Table 1 gives radiation characteristics of ^{60}Co. We do simulation by considering γ-rays at these two different energies and at an averaged energy of 1.25 MeV. Our simulation shows that the difference in the energy deposition for γ-rays at these different energies is not significant. Thus in the following we only display the results obtained for γ-rays of 1.333MeV.

Table 1 Radiation characteristic of ^{60}Co

Symbol	Half life (a)	Disintegration type and energy (MeV)		Production method
		β	γ	
^{60}Co	5.263(63)	0.318(99.9%)	1.173(99.86%)	$^{59}Co(n, \gamma)$
		1.491(0.1%)	1.333(99.98%)	$^{59}Co(d,p)$

We assumed that the radiate region has a spherical shape, thus the situation can be modeled as a water-ball with center region being the radiate part and the other areas being the surrounding areas. The water ball in the simulation was divided evenly into N shells with each shell thickness to be $(R–R_c)/N$, where R and R_c are the radius of the water ball and the radiate region, respectively. In most cases, we choose N=100. The energy deposition is integrated for each shell. The radius of the water ball was chosen to be 15 cm.

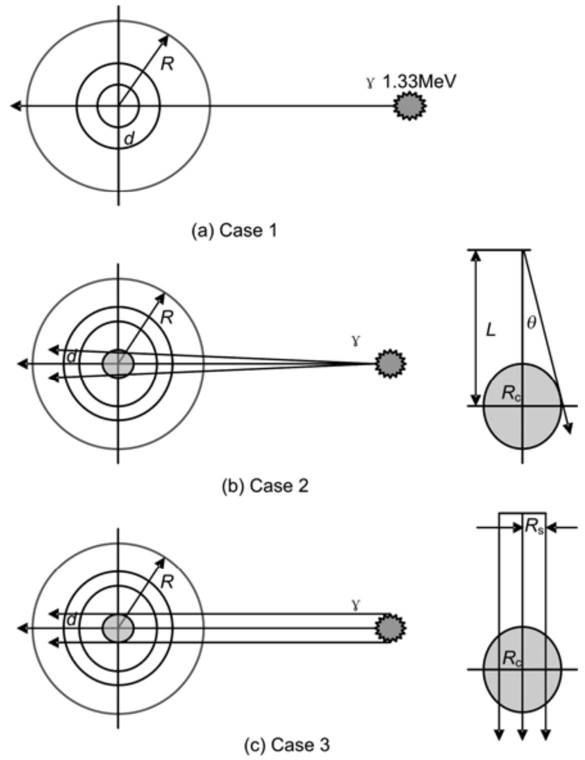

Fig.2 Various γ-ray source-water ball configurations.

We first focus on the γ-ray radiation from the source. We considered three simplest possible cases. The first one is that the radiation source is a point source and the radiated γ-ray is perfectly collimated, (in this model we assume that the point source is a perfect point, so the γ-ray radiation from the source is also a perfect beeline) as shown in Fig.2(a). The second case is that the γ radiation source is a point source, but the radiated γ-ray is spread over an angle θ, and the angle θ satisfies $\sin\theta=R_c/L$, where R_c is the radius of the malignant tissues, as shown in Fig.2(b).The third case is that radiated γ-ray remains to be perfectly collimated, but the size of the source and the beam to be a nonzero R_s as shown in Fig.2(c). A combination of the second and the third cases allows one to resemble a case close to a realistic radiation source.

4 Results and discussions

From the simulation, we got the energy deposited (GeV) of different radial shell and the average energy density deposited (GeV/cm^3) in a given shell. For case 1 and case 2, when calculating the density, since what we care is only the comparative tendency, we can ignore the constant 4π/3 and R^3. Table 2 and Table 3 display respectively the results of case 1 and case 2. From the values under the different ratio of $\varepsilon/\varepsilon_0$ (where ε is energy density deposited in a given shell and ε_0 is the averaged energy density deposited in the malignant region) on the different radiate region size, we can obtain that if the radiate region size increases, energy density deposited in a given shell falls off slower and slower as the radius increases. For example, for case 1, if the radiate region diameter is 0.03cm, the value $\varepsilon/\varepsilon_0$ falls off to 1/10000 at the 0.93cm to the center of radiate region. But if the radiate region diameter is 0.3cm, the value $\varepsilon/\varepsilon_0$ falls off to 1/100 at the 1cm to the center of radiate region and reaches to 1/10000 at the 12cm to the center. So it means that the larger the radiate region size is, the more serious the damage to the area surrounding radiate region is.

Table 2 Simulation result in case 1 (R=15.0 cm)

Malignant region radius	n	$\varepsilon/\varepsilon_0$				$\varepsilon/\varepsilon_0$ at 15cm
		1/10	1/100	1/1000	1/10000	
0.015 cm	1000	0.035 cm	0.1 cm	0.3 cm	0.93 cm	~1/1916000
0.025 cm	600	0.062 cm	0.152 cm	0.47 cm	1.59 cm	~1/713000
0.03 cm	500	0.074 cm	0.19 cm	0.58 cm	1.98 cm	~1/470400
0.0375 cm	400	0.091 cm	0.244 cm	0.73 cm	2.5 cm	~1/293000
0.05 cm	300	0.12 cm	0.32 cm	1.0 cm	3.6 cm	~1/165340
0.075 cm	200	0.18 cm	0.48 cm	1.54 cm	5.66 cm	~1/68900
0.15 cm	100	0.35 cm	0.95 cm	3.4 cm	12.15 cm	~1/16600

Table 3 Simulation result in case 2 (R=15.0 cm, source rays spread over an angle θ)

Malignant region radius	n	$\varepsilon/\varepsilon_0$				$\varepsilon/\varepsilon_0$ at 15cm
		1/10	1/100	1/1000	1/10000	
1.0 cm	100	2.3 cm	8.6 cm			~1/300
1.0 cm	1000	2.3 cm	8.6 cm			~1/366
0.9 cm	100	2.16 cm	7.75 cm			~1/379
0.8 cm	100	1.87 cm	6.7 cm			~1/487
0.7 cm	100	1.65 cm	5.85 cm			~1/617
0.6 cm	100	1.43 cm	4.9 cm			~1/819
0.5 cm	100	1.18 cm	4.03 cm	14.2 cm		~1/1200
0.5 cm	1000	1.1 cm	3.9 cm	14.2 cm		~1/1440
0.4 cm	100	0.95 cm	3.1 cm	11.35 cm		~1/1825
0.3 cm	100	0.74 cm	2.3 cm	8.3 cm		~1/3300
0.2 cm	100	0.49 cm	1.5 cm	5.2 cm		~1/7500
0.1 cm	100	0.26 cm	0.75 cm	2.4 cm	8.9 cm	~1/30000
0.05 cm	300	0.1 cm	0.35 cm	1.1 cm	3.95 cm	<1/100000

Fig.3 and Fig.4 display the radial distance of the given shell to the center of the ball(R) (it means relative energy density deposited) versus the radius of the radiate region (R_c) in the case 1 and case 2. The different curves correspond to different values of ratio $\varepsilon/\varepsilon_0$. From the two figures, R goes up as R_c increases and the relationship between the two variables is linear.

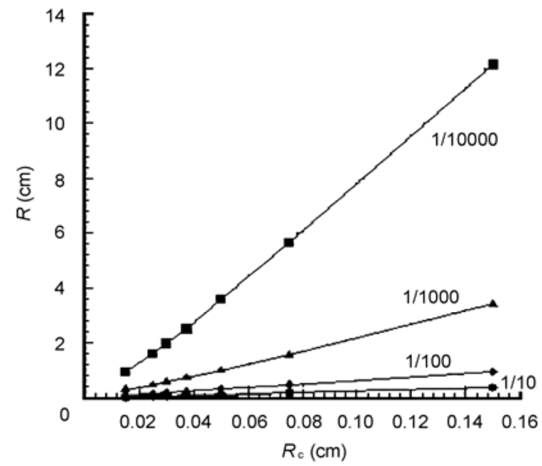

Fig.3 Relationship between relative energy density deposited and radius of the malignant region in case 1.

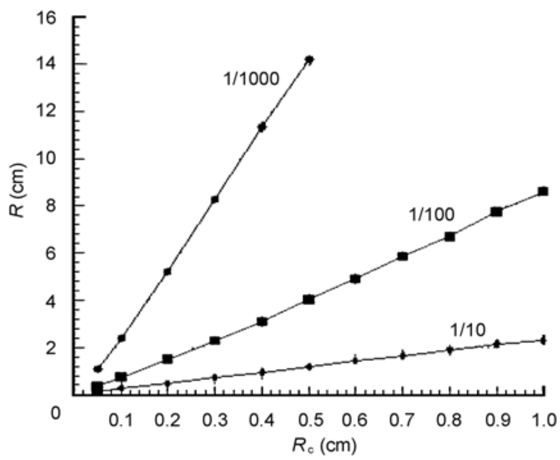

Fig.4 Relationship between relative energy density deposited and radius of the malignant region in case 2.

In case 3, we must consider the source size (R_s). Table 4 shows the simulation results if keeping R_s constant. Fig.5 displays the relationship between R and R_c. Its shape is the same as the cases 1 and 2. Table 5 shows the results if keeping R_c constant. The corresponding Fig.6 illustrates the relationship between R and R_s. It shows that the effect of R_s on the energy density deposited is very small. From the figure, we can see that if R_s increases ten times when the value of $\varepsilon/\varepsilon_0$ is a constant, the variation of R is no more than 15%.[5]

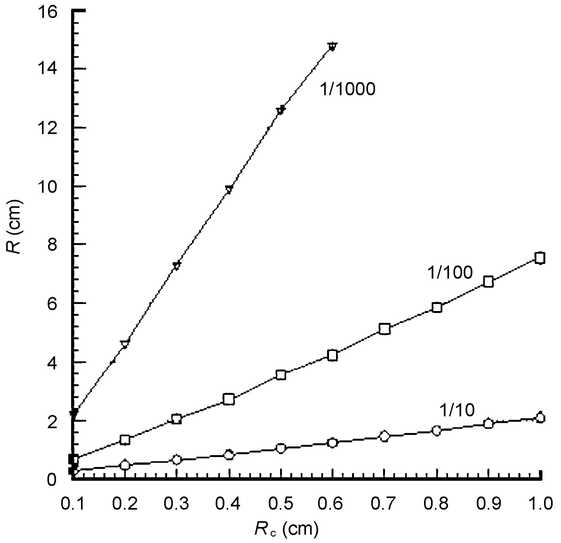

Fig.5 Relationship between relative energy density deposited and radius of the malignant region in case 3.

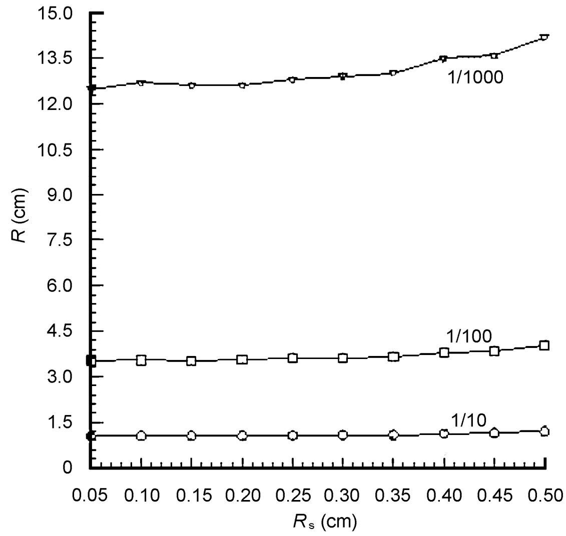

Fig.6 Relationship between relative energy density deposited and radius of the source size in case 3.

Table 4 Simulation result in case 3 (R_c is malignant region radius, R_s is radiated source radius)

R_c	R_s	N	$\varepsilon/\varepsilon_0$				$\varepsilon/\varepsilon_0$ at 15cm
			1/10	1/100	1/1000	1/10000	
1.0 cm	0.01 cm	100	2.07 cm	7.55 cm			~1/390
0.9 cm	0.01 cm	100	1.88 cm	6.74 cm			~1/480
0.8 cm	0.01 cm	100	1.65 cm	5.85 cm			~1/600
0.7 cm	0.01 cm	100	1.45 cm	5.13 cm			~1/790
0.6 cm	0.01 cm	100	1.23 cm	4.23 cm	14.8 cm		~1/1080
0.5 cm	0.01 cm	100	1.04 cm	3.54 cm	12.6 cm		~1/1490
0.4 cm	0.01 cm	100	0.82 cm	2.71 cm	9.9 cm		~1/2330
0.3 cm	0.01 cm	100	0.65 cm	2.03 cm	7.3 cm		~1/4140
0.2 cm	0.01 cm	100	0.46 cm	1.33 cm	4.6 cm		~1/9400
0.1 cm	0.01 cm	100	0.27 cm	0.69 cm	2.2 cm	7.8 cm	~1/39200

Table 5 Simulation result in case 3 (considering the effect of R_s)

R_c	R_s	N	$\varepsilon/\varepsilon_0$				$\varepsilon/\varepsilon_0$ at 15cm
			1/10	1/100	1/1000	1/10000	
0.5 cm	0.50 cm	100	1.19 cm	4.04 cm	14.2 cm		~1/1190
0.5 cm	0.45 cm	100	1.14 cm	3.84 cm	13.6 cm		~1/1270
0.5 cm	0.40 cm	100	1.12 cm	3.79 cm	13.5 cm		~1/1310
0.5 cm	0.35 cm	100	1.08 cm	3.64 cm	13.0 cm		~1/1390
0.5 cm	0.30 cm	100	1.08 cm	3.61 cm	12.9 cm		~1/1410
0.5 cm	0.25 cm	100	1.06 cm	3.61 cm	12.8 cm		~1/1460
0.5 cm	0.20 cm	100	1.05 cm	3.57 cm	12.6 cm		~1/1500
0.5 cm	0.15 cm	100	1.05 cm	3.52 cm	12.6 cm		~1/1500
0.5 cm	0.10 cm	100	1.05 cm	3.54 cm	12.7 cm		~1/1490
0.5 cm	0.05 cm	100	1.04 cm	3.53 cm	12.5 cm		~1/1490

5 Conclusions

The results presented in this paper show that energy deposition in unit volume, caused by a radiated γ-ray, decreases with the increase of distance of the position to the center of radiate region. The larger the radiate region is, the stronger the effects on the surrounding regions are. However, the effects will be smaller when a well-collimated beam is used comparing to a dispersed beam.

Although the situation in which the numerical simulation was conducted may be over-simplified, these results probably provide a base for carrying out elaborated simulations which are much more close to realistic situation such as radiation protection and radiation therapy.

References

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