



The Electron-dose Distribution Surrounding An ^{192}Ir Wire Brachytherapy Source Investigated using EGS4 Simulations and GafChromicTM Film

Y. C. CHEUNG¹, PETER K. N. YU¹, E. C. M. YOUNG¹, C. L. CHAN²,
M. F. NG², FRANCIS N. F. TANG² and TONY P. Y. WONG³

¹Department of Physics and Materials Science, City University of Hong Kong, Kowloon, Hong Kong, ²Department of Radiotherapy and Oncology, Queen Elizabeth Hospital of Hong Kong, Hong Kong and ³Austin & Repatriation Medical Centre, Victoria 3081, Australia

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The steep dose gradient around ^{192}Ir brachytherapy wire implants is predicted by the EGS4 (PRESTA version) Monte Carlo simulation. When considering radiation absorbing regions close to the wire source, the accurate dose distribution cannot be calculated by the GE Target II Sun Sparc treatment-planning system. Experiments using GafChromicTM film have been performed to prove the validity of the EGS4 user code when calculating the dose close to the wire source in a low energy range. © 1997 Elsevier Science Ltd

Introduction

Small-wire brachytherapy sources are being used more and more to treat intravascular lesions and, for example, the walls of arteries in combination with angioplasty to prevent restenosis. With the help of the Monte Carlo method and a new radiochromic film, the dose close to the ^{192}Ir wire source is unveiled.

There is a new radiochromic film "GafChromicTM Dosimetry Media" which is distributed by Nuclear Associates. According to Muench *et al.* (1991), the GafChromicTM film (type DM 1260) is a highly uniform thin (100 μm) detector, whose sensitive coated layer (6 μm thick) changes from colorless to blue by dye polymerization without processing upon exposure to ionizing radiation.

When monochromatic densitometry at the wavelength 632.8 nm (He-Ne Laser) is used, the response of the net optical density (the optical density minus that of an unexposed film) versus the dose for radiation energy from 28 keV to 1.71 MeV is linear up to a dose of about 150 Gy. Furthermore, the dependence on the photon energy in this energy range is slight. The GafChromicTM film is sensitive to ultraviolet light, which is also produced by some sources of visible light. Therefore, the film should be stored in the dark. For optimum life, it should be stored at a temperature below 25°C and a relative humidity below 50%.

The operational characteristics of the GafChromicTM film have been evaluated by Saylor *et al.* (1988) and McLaughlin *et al.* (1991), who reported good uniformity for the radiochromic sensor coating and good reproducibility for individual film measurements. The response of the film over the dose range from 100 to 5000 Gy has been studied using scanning visible spectrophotometry, color photometry, densitometry and scanning densitometry. It has also been found to be essentially insensitive to visible light at wavelengths above 300 nm. According to McLaughlin *et al.* (1991), the base of the film is a 100 μm thick clear polyester film; the film is colorless and "grainless" in that its radiographic image gives a spatial resolution of > 1200 lines/mm; and the density of the 6 μm GafChromicTM sensor material is 1.3 g/cm and its constituent factors by weight are H(0.0897), C(0.6058), N(0.1122) and O(0.1923). Furthermore, the response to electrons in terms of increase in absorbance per unit absorbed dose is the same as that to gamma radiation within the estimated uncertainty of the measurements ($\pm 5\%$, 95% confidence level).

The particular advantage of the film is its ability to record the incidence of radiation at closely spaced points simultaneously and close to the source. In the present work, GafChromicTM film is used to perform a benchmark experiment to verify the validity of the EGS4 user code which predicts the steep dose

gradient close to the ^{192}Ir wire source in the low energy range. The steep dose gradient in absorbing media close to the source cannot be predicted by most treatment planning systems (e.g. GE Target II) since only exiting photons are focused and the Meisberger polynomial (Meisberger *et al.*, 1968) employed in the algorithm of the treatment-planning systems may not predict accurately the ratio of exposure in water to that in air for radial distances less than 1 cm. Moreover, the volume elements (Cassell, 1983) employed in the algorithm is also one of the limitations.

Experimental Setup

The film employed is type MD-55 with Cat. No. 37-041, and is manufactured by ISP Technologies Inc. (available from Victoreen Inc., 100 Voice Road, P.O. Box 349, Carle Place, NY 11514-0349). In Fig. 1, two slabs of GafChromic™ film have been placed at the surface of an ^{192}Ir wire source, which has an activity of 2.9 mCi/cm, with the sensor layer facing towards the wire source. The ^{192}Ir wire source is made straight by an elastic string at one end. The setup is shown in Fig. 2. Hooks are made at the ends of the wire and are kept strong by two plastic caps (see Fig. 3). The original length was 56 mm, with 3 mm at each end used to make hooks. The length of the exposed wire (i.e. not covered by the plastic caps) is 44 mm. It is assumed that the plastic caps and the hooks will not affect the dose registered on the films since the films are placed very close to the ^{192}Ir wire source.

The setup is stored in a dark environment with a low radiation background of 2–3 $\mu\text{Gy/h}$. The irradiation time is 3.28 h (short irradiation time). Another setup is repeated for an irradiation time of 60.98 h (long irradiation time). The activity of the ^{192}Ir wire source has been decaying during the measurements and therefore the measured results should be corrected by dividing a time integral of $\int_{t_1}^{t_2} \exp(-\ln 2/T_{1/2} \cdot t) \cdot dt$ where t_1 is the irradiation start

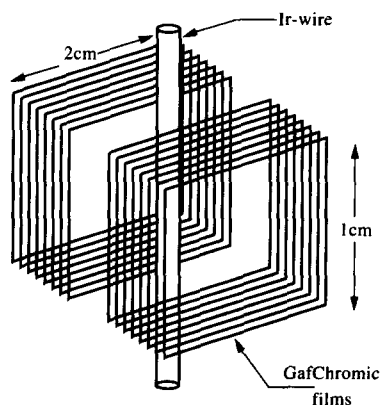


Fig. 1. Schematic diagram to illustrate the setup for measuring the dose gradient close to the Ir wire source.

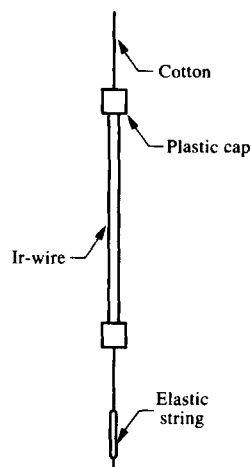


Fig. 2. The setup to make the wire straight.

time and t_2 is the irradiation completion time. The half life $T_{1/2}$ of ^{192}Ir , according to Podgorsak *et al.* (1993), is 73.83 days. In Table 1, we have shown the values of t_1 and t_2 for the time integral during irradiation. The longer irradiation time darkens the films seriously and causes less uncertainty when the optical density of the films is read. However, the films might have saturation if they are placed too close to the surface of the source.

The intensity transmitted through the film is measured using a 0.95 mW He–Ne laser light source (Novette™) and a photodiode (Newport Model 818-SL) connected to a Newport Digital Power Meter (Model 815 series). The spot size is 0.48 mm in diameter and the wavelength is 632.8 nm. No optical filter is used and a slit is placed in front of the detector to resolve the film image. The slit is formed by two sheets of black paper placed very close to each other. The film is scanned along a track as shown in Fig. 4 so that a minimal intensity is measured. A light increase due to this width does not cause significant changes to the measured net optical density, and therefore the present slit is fine enough to resolve the films even when the films are placed very close to the wire source. In order to obtain a stable readout, the whole setup is used after a warming-up period of more than 30 min. Its uncertainty is found by reading the power meter several times without the insertion of

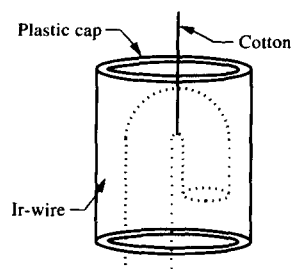


Fig. 3. The schematic diagram showing the ends of the Ir wire source.

Table 1. Values of irradiation start time t_1 and irradiation completion time t_2 for the measurements of the different irradiation times (hours)

	t_1	t_2	Time integral
Short irradiation time	360.32	363.60	2.84
Long irradiation time	363.62	424.60	52.3

the film, which is 9.4%. The intensity is then converted to the net optical density.

All the GafChromic™ films (2×1 cm) were measured in one session for accurate comparisons after a waiting period of more than 1 day after exposure. A micrometer was used to measure the thickness of the films. When five samples were examined, the overall thickness of one film was 0.119 ± 0.001 mm. Since the GafChromic™ layer is soluble in water, the thickness of the base was found to be 0.103 ± 0.001 mm and the thickness of the GafChromic™ layer was 0.0152 ± 0.0004 mm. The mass and the volume of the films were known, so the density of the GafChromic™ layer and the base were found to be 1.202 ± 0.063 g/cm³ and 1.360 ± 0.014 g/cm³, respectively. These data are particularly useful in running the EGS4 Monte Carlo simulation.

Monte Carlo Simulation

The above setup is simulated by the EGS4 (PRESTA version) (Bielajew and Rogers, 1988) Monte Carlo code. One can refer to Nelson *et al.* (1985) for the structure of the EGS4. The host computer employed in the present investigation is based on an Intel™ 80486 cpu and operates under version 5 of the MS-DOS™. The computer operates at a clock speed of 33 MHz. The ¹⁹²Ir wire source is modeled by two 5 cm long concentric cylinders. For a radial symmetry, the films are modeled by some 1 cm high concentric cylinders around the wire source. The energy deposition of the particles is scored within the sensor layer (5 mm high at the middle of the 1 cm high concentric cylinders). Figure 5 shows the details of the geometry for the EGS4. The different shape of the films used in the EGS4 (Fig. 5) is assumed to give the same results of those in the experiment (Fig. 1), since the films are placed very close to the source so that the effects on the absorbed dose due to the excess film materials in

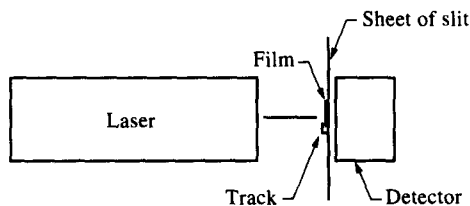


Fig. 4. The setup to measure the film with He-Ne laser beam scanning.

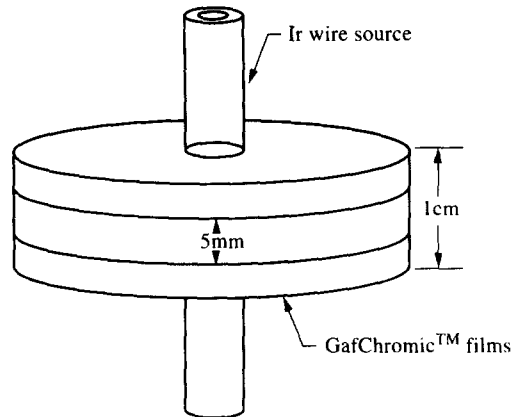


Fig. 5. The geometry used in the EGS4 computation.

the experiment are small when compared to the high dose rate close to the source.

The following are the PEGS4 (pre-processor of the EGS4) input files for the sensor material and the polyester base of the film, respectively, which are used to create a data set for the simulation in the energy range between 2 keV and 1.1 MeV. These input files are based on those given by Nelson (1989).

```
MIXT& INP NE = 4,RHO = 1.2017,RHOZ
= 8.97,60.58,11.22,19.23,IRAYL
= 1&ENDGAFCHROMICH C N OENER& INP
AE = 0.513,UE = 1.611,AP = 0.002,UP
= 1.10 &ENDTEST&INP &ENDPWLF&INP
&ENDDECK&INP &ENDCOMP&INP NE
= 3,RHO = 1.3596,PZ = 8.4,10,IRAYL
= 1 &ENDPET PETH O CENER&INP AE
= 0.513,UE = 1.611,AP = .002,UP
= 1.10 &ENDTEST&INP &ENDPWLF&INP
&ENDDECK&INP &END
```

PEGS4 does not allow the value of AE to be smaller than 0.513. An error will occur if the value of AE is wrongly set. PEGS4 will run successfully even when the value of AP is set down to 0.001. ECUT and PCUT are the cutoff energies in MeV of the electrons and photons and are 0.515 and 0.004, respectively. It is assumed that the absorbed dose due to β -rays from the ¹⁹²Ir wire source is small and negligible because of the Pt encapsulation. Therefore, the EGS4 calculations do not consider the exiting β -rays.

Results and Discussion

The intensity or power measured is converted into optical density, which is defined as $\log_{10}(I_0/I_1)$, where I_0 is the intensity of visible light incident upon a small area of the film and I_1 is the intensity of light transmitted through that region of the film (Fig. 6). Figure 7 shows the comparisons of optical densities measured by the GafChromic™ film (long irradiation time: 52.3 h normalized; short irradiation time: 2.84 h normalized) and calculated by the EGS4. Since

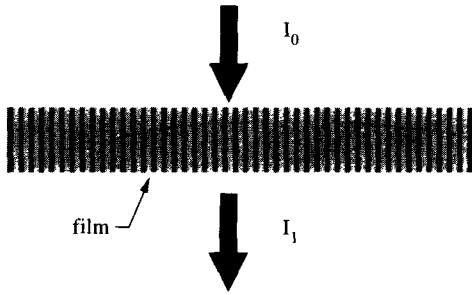


Fig. 6. The intensities I_0 and I_1 used for the calculation of the optical density.

the EGS4 calculation only give us the information of the absorbed dose rate at a certain radial distance, the net optical density in column 5 of the Table 2 is obtained by normalizing the EGS4 results of the absorbed dose to the results of the net optical density of the GafChromic™ film at the radial distance of 1.581 mm. Since the net optical density is proportional to the absorbed dose, the EGS4 Monte Carlo simulation can tell us the net optical density at any radial distance from the wire source in the film materials. In order to obtain the results with minimal uncertainty and at the same time to prevent saturation at small radial distances, two different irradiation times were employed in the experiment.

The results listed in Table 2 are also shown in

Fig. 7. At small radial distances, the curves of the EGS4 calculation and the experiment (2.84 h, normalized) drop more rapidly with radial distance because of the large amount of attenuation of the exiting secondary electrons due to the Pt encapsulation. The exiting β -rays do not contribute to any observable effects of the absorbed dose near the wire source and the assumption that the β -rays have negligible effect is therefore justified.

The response curve for the GafChromic™ film with the normalized irradiation time of 52.3 h shows small uncertainties when compared to that of 2.84 h. Moreover, the former results show a saturation within the radial distance of 0.678 mm, so the relationship between net optical density and the absorbed dose is no longer linear above 301.7 Gy for the ^{192}Ir wire source. The maximum absorbed dose of the curve with the normalized irradiation time of 2.84 h is limited to 168.9 Gy so that linearity is ensured.

From Fig. 7, we observe that the results of the EGS4 are consistent with those of GafChromic™ film, except at a point on the surface where the GafChromic™ film has a smaller result than that calculated by the EGS4, which is mainly due to the difference in the geometry between the experiment and the EGS4. By comparing Figs 8 and 9, we see that the lack of film materials (the unshaded area in

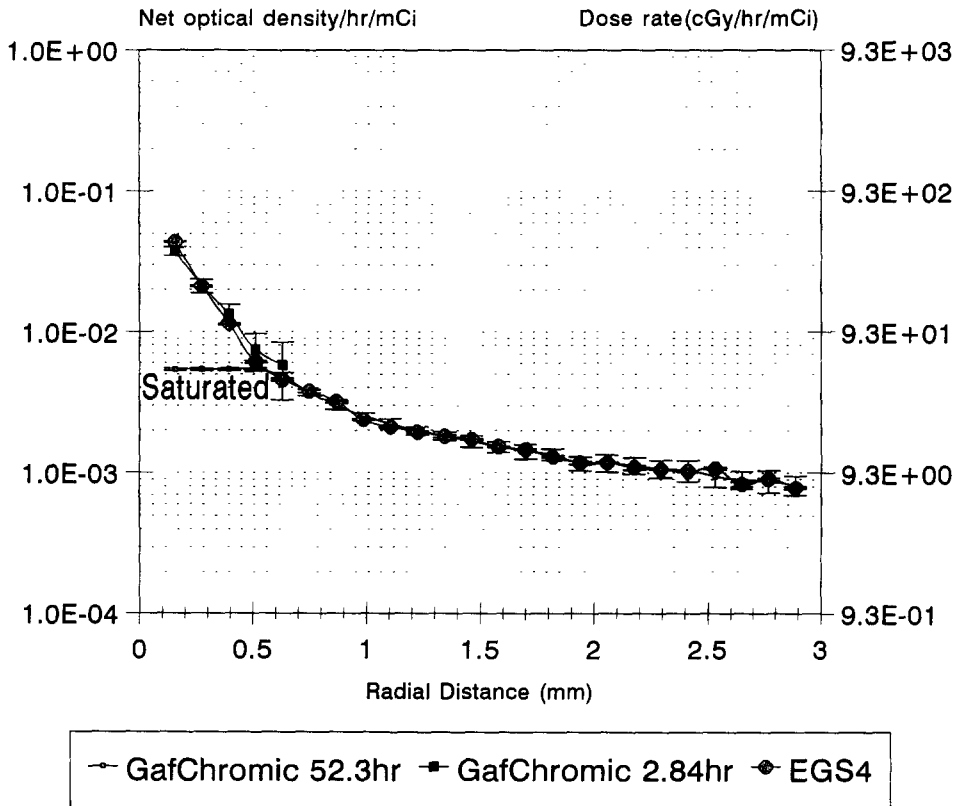


Fig. 7. Comparison of the dose gradients measured by the GafChromic™ film (long and short normalized irradiation times of 52.3 and 2.84 h) and calculated by EGS4.

Table 2. Comparisons of the optical densities measured by the experiment (GafChromic™ film) and calculated by the EGS4

Radial distance (cm)	Net optical density/h/mCi for the experiment with 52.3 normalized irradiation time	Net optical density/h/mCi for the experiment with 2.84 normalized irradiation time	Dose rate (cGy/h/mCi) calculated by EGS4	Net optical density/h/mCi calculated by EGS4
0.0158	5.40E - 03 ± 1.08E - 04	3.75E - 02 ± 2.67E - 03	382.44 ± 5.34	4.09E - 02 ± 5.71E - 04
0.0276	5.40E - 03 ± 1.08E - 04	2.12E - 02 ± 2.39E - 03	197.76 ± 1.40	2.12E - 02 ± 1.50E - 04
0.0395	5.40E - 03 ± 1.08E - 04	1.34E - 02 ± 2.27E - 03	113.76 ± 0.96	1.22E - 02 ± 1.02E - 04
0.0514	5.40E - 03 ± 1.08E - 04	7.45E - 03 ± 2.23E - 03	63.02 ± 0.76	6.74E - 03 ± 8.09E - 05
0.0632	4.77E - 03 ± 3.07E - 04	5.82E - 03 ± 2.58E - 03	47.38 ± 0.71	5.07E - 03 ± 7.61E - 05
0.0751	3.68E - 03 ± 1.95E - 04	4.77E - 03 ± 2.11E - 03	39.91 ± 0.44	4.27E - 03 ± 4.73E - 05
0.0870	2.99E - 03 ± 2.08E - 04	3.62E - 03 ± 2.26E - 03	28.57 ± 0.51	3.06E - 03 ± 5.48E - 05
0.0988	2.53E - 03 ± 1.18E - 04	3.71E - 03 ± 2.50E - 03	23.74 ± 0.48	2.54E - 03 ± 5.19E - 05
0.1107	2.23E - 03 ± 1.72E - 04	2.72E - 03 ± 2.33E - 03	22.29 ± 0.62	2.39E - 03 ± 6.67E - 05
0.1225	1.98E - 03 ± 1.32E - 04	2.87E - 03 ± 2.39E - 03	19.82 ± 0.27	2.12E - 03 ± 2.93E - 05
0.1344	1.83E - 03 ± 1.23E - 04	2.19E - 03 ± 2.08E - 03	18.46 ± 0.35	1.98E - 03 ± 3.71E - 05
0.1463	1.67E - 03 ± 1.61E - 04		15.15 ± 0.42	1.62E - 03 ± 4.50E - 05
0.1581	1.53E - 03 ± 1.35E - 04		14.33 ± 0.27	1.53E - 03 ± 2.92E - 05
0.1700	1.42E - 03 ± 1.66E - 04		13.21 ± 0.36	1.41E - 03 ± 3.87E - 05
0.1819	1.35E - 03 ± 1.25E - 04		13.61 ± 0.20	1.46E - 03 ± 2.13E - 05
0.1937	1.17E - 03 ± 1.29E - 04		11.29 ± 0.22	1.21E - 03 ± 2.31E - 05
0.2056	1.18E - 03 ± 1.64E - 04		10.82 ± 0.14	1.16E - 03 ± 1.48E - 05
0.2175	1.13E - 03 ± 1.51E - 04		10.52 ± 0.26	1.13E - 03 ± 2.74E - 05
0.2293	1.07E - 03 ± 1.49E - 04		10.03 ± 0.27	1.07E - 03 ± 2.92E - 05
0.2412	1.04E - 03 ± 1.77E - 04		9.24 ± 0.18	9.89E - 04 ± 1.90E - 05
0.2531	9.48E - 04 ± 1.55E - 04		8.45 ± 0.11	9.04E - 04 ± 1.23E - 05
0.2649	8.98E - 04 ± 1.28E - 04		8.54 ± 0.13	9.14E - 04 ± 1.34E - 05
0.2768	8.79E - 04 ± 1.59E - 04		8.23 ± 0.11	8.81E - 04 ± 1.22E - 05
0.2887	8.22E - 04 ± 1.28E - 04		7.06 ± 0.23	7.55E - 04 ± 2.43E - 05

Fig. 8) surrounding the ^{192}Ir wire source in the experiment has caused less scattering within the films and therefore less absorbed dose registered by the film at the surface of the wire source. In conclusion, with the use of the GafChromic™ film, it can be proved that the user code of the EGS4 can produce correct results at small radial distances and in the low electron energy range. With the help of the Monte Carlo technique, the dose rate near the surface of the ^{192}Ir source which was unknown in the past can now be revealed. Of course, the same technique can be applied to other brachytherapy sources to explore the dose rates in absorbing media close to the source.

The EGS4 user code used for simulating the GafChromic™ film is now modified to calculate the dose distribution in water. The dimensions of the cylinders employed in the EGS4 geometry are enlarged to obtain larger radial distances and the GafChromic™ film in the EGS4 is replaced by water. The following is the input file of PEGS4 used to create a data set for water between 2 keV and

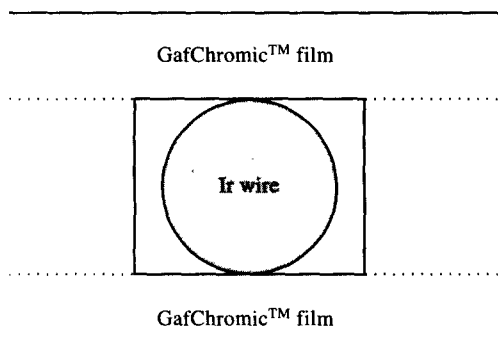


Fig. 8. The schematic diagram showing the partial lack of film materials around the Ir wire source in the experiment.

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1.1 MeV:COMP&INP NE = 2,RHO = 1.0,PZ
= 2.1,IRAYL = 1 &ENDH2O H2OH
OENER&INP AE = 0.513,UE = 1.611,AP
= .002,UP = 1.10 &ENDTEST&INP
&ENDPWLF&INP &ENDDECK&INP &END
```

In Fig. 10, the Monte Carlo results of the absorbed dose rate versus the radial distance in water are shown, together with the results calculated by the GE Target II Sun Sparc treatment-planning system. The GE Target II Sun Sparc treatment-planning system can only reproduce the EGS4 results at radial distances greater than about 1.6 mm, because the algorithm of the GE Target II focuses only on the exiting photons. Since the exposure-to-rad conversion factor employed by the GE Target II is 0.957 (ICRU, 1963), a conversion factor 0.974/0.957 is introduced for a comparison between the results of

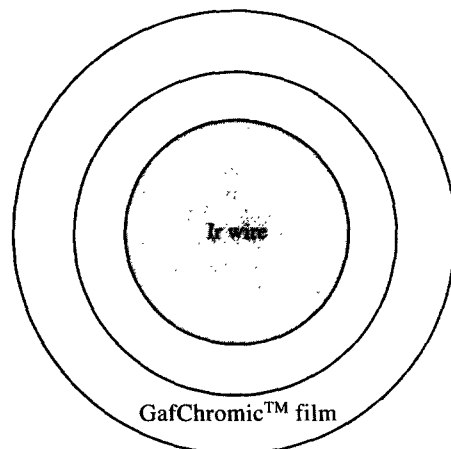


Fig. 9. The schematic diagram showing the presence of films closely around the Ir wire source in the EGS4 simulation.

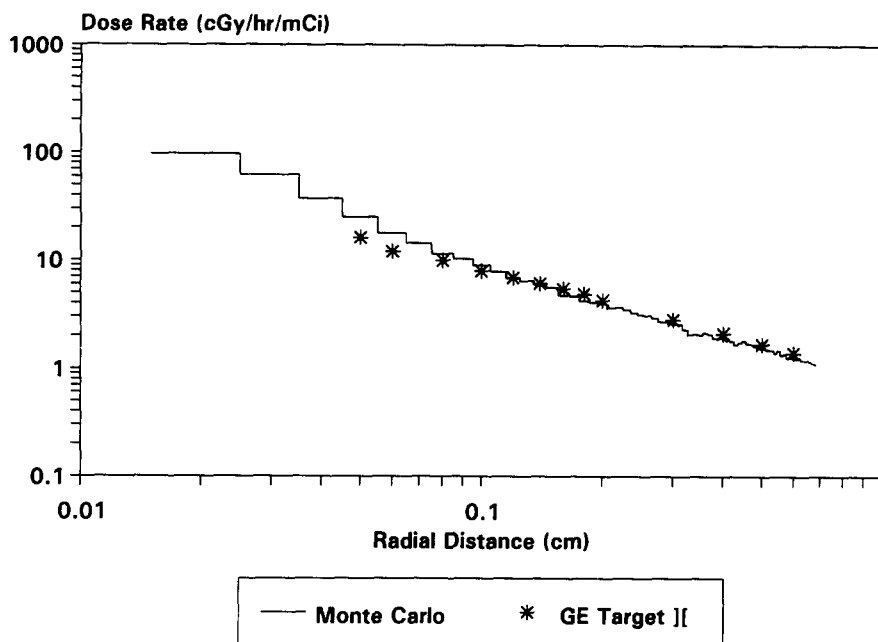


Fig. 10. The Monte Carlo results of the absorbed dose rate versus the radial distance in water, together with the results calculated by GE Target II Sun Sparc treatment-planning system.

the GE Target II and the EGS4 simulation in water, with the value of 0.974 adopted from Schauer and Links (1993) at an average energy of 300 keV. Since the conversion factor 0.974/0.957 is nearly unity, such a correction is not very important. Moreover, the finite size of the volume elements used in the algorithm employed by the GE Target II is also one of the limitations in the calculation of the dose distribution near the surface of the wire source.

The Monte Carlo results of the dose distribution close to the ^{192}Ir wire source in Fig. 10 are difficult to obtain through measurements and the calculated enhanced-dose due to the secondary electrons exiting from the Pt-encapsulation can serve as a reference for radiologists and medical physicists.

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