DOSE RATE DISTRIBUTIONS FOR ^{103}PD, ^{125}I, ^{169}YB AND ^{192}IR BRACHYTHERAPY SOURCES. AN EGS4 MONTE CARLO STUDY.

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ABSTRACT

Absolute dose rate distributions in water around ^{103}Pd, ^{125}I, ^{169}Yb and ^{192}Ir brachytherapy sources were estimated by mean of the EGS4 Monte Carlo Simulation System. DLC-136/PHOTX cross section library, water molecular form factors, bound Compton scattering and Doppler broadening of the Compton-scattered photon energy were considered in the calculations. Following AAPM recommendations for dosimetry of interstitial brachytherapy sources, dose rate constants, radial dose functions and anisotropy functions have been calculated. Comparison of absolute dose rate values computed after the protocol recommended by the AAPM Task Group No. 43 between their proposed values and our Monte Carlo calculated values shows excellent agreement between both data sets. Moreover, Monte Carlo-based dosimetry data can be used as alternative to measured values offering reliable and accurate values, thus validating them as an emerging clinical dosimetry tool.

1. INTRODUCTION

Accurate knowledge of dose distribution around radioactive sources employed in interstitial brachytherapy implants is necessary in order to provide a solider basis when developing a clinical strategy. The AAPM Task Group No.43 recommends a dosimetry protocol based on measured (or measurable) quantities [26] allowing for two-dimensional dose calculations around cylindrically symmetric sources. Decoupling of various physical factors is chosen by introducing radial dose functions and anisotropy function; both of which are relative quantities. Because of their relative nature, the uncertainties in their determination are reduced. Another advantage of this decoupling is that when more accurate values become available, they can be easily accommodated in a revision of the protocol.

Measurement of dose distributions is usually performed in "water equivalent" solid plastic phantoms. They have the advantage that they can be precisely machined to accommodate sources and detectors, and distances can be accurately determined. Those plastic phantoms are intended to

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match the total attenuation coefficients and stopping powers of liquid water over a wide range of photon energies. Williamson [43] showed that solid water does not reproduce the scattering and absorption cross sections of liquid water in the low energy range (^{125}I and ^{103}Pd sources), thus resulting in an underestimation of the radiation penetrability in water. Accurate dose measurements in the vicinity of individual brachytherapy sources is difficult. Conventional ion chambers either lack the sensitivity to measure accurately the low levels of radiation emanating from individual sources, or are so large that dose gradients across the sensitive volume compromise spatial resolution. Solid state dosimeters, such as diodes, radiographic film, or thermoluminescent dosimeters (TLD), provide the necessary sensitivity and spatial resolution, but exhibit energy dependent responses which will vary with the source energy and with the position of the dosimeter within an absorbing medium [6, 9].

The most common computational implementation of transport theory is Monte Carlo photon transport simulation. An important development of the last decade has been validation and acceptance of Monte Carlo simulation as an accurate and reliable source of clinically-useful dosimetry data.

The availability of more accurate photon cross section libraries and the existence of well-tested and well-documented Monte Carlo computer codes developed at national laboratories and available in the public domain made the Monte Carlo approach feasible.

In this study we present Monte Carlo calculated dose rate distributions for several brachytherapy sources and compare them with experimental and theoretical results reported in the literature with the purpose to use them directly for clinical treatment planning following the formalism recommended by the AAPM Task Group No.43 [26]. Our Monte Carlo results are given in term of absolute dose rate per unit activity in medium in units of Gy s^{-1} Bq^{-1} . Throughout this paper we will refer to ^{103}Pd and ^{125}I sources as low energy sources and to ^{169}Yb and ^{192}Ir sources as high energy sources.

2. MATERIALS AND METHODS

2.1. Dose calculation formalism

The AAPM Radiation Therapy Committee Task Group No.43 [26] recommends a formalism developed by the Interstitial Brachytherapy Collaborative Working Group [9] to predict the two-dimensional dose distribution around cylindrically symmetric sources using only measured data, although it can equally well be used with theoretically calculated data. The dose rate at a point (r,θ) relative to the geometric center of the source is given by

$$\dot{D}(r,\theta) = S_k \cdot \Lambda \cdot G(r,\theta) / G(r_0,\theta_0) \cdot g(r) \cdot F(r,\theta) \quad (1)$$

where r is the distance to the point of interest; θ is the angle with respect to the longitudinal axis of the source; S_k is the air kerma strength of the source, a measure of brachytherapy source strength, specified in terms of air kerma rate at a point along the transverse axis of the source in free space; Λ is the dose rate constant, defined as the dose rate to water at a distance of 1 cm on the transverse axis of a unit air kerma strength source in a water phantom; $G(r,\theta)$ is the geometry distribution given in cm^{-2} accounting for spatial distribution of radioactive material; $F(r,\theta)$ is the anisotropy function that accounts for the angular dependence of photon absorption and scatter in the encapsulation and the medium; and *g(r)* is the radial dose function that accounts for radial dependence of photon absorption and scatter in the medium along the transverse axis ($\theta = \pi/2$).

For a more detailed description of the formalism the reader is referred to the Task Group 43 report or the paper by Williamson and Nath [Williamson and Nath 1991].

2.2. Monte Carlo calculations with EGS4 system

The EGS4 user code DOSRZ [1] was modified to allow simulation of the complex internal seed structure of cylindrical brachytherapy seeds. The photon cross section compilation, DLC-136/PHOTX [33] contributed by the National Institute of Standards and Technology and implemented for EGS4 use by Sakamoto [34] was employed in the calculations. Bound Compton scattering and Doppler broadening of the Compton-scattered photon energy were considered in the calculations by including the Low-Energy Photon-Scattering Expansion for the EGS4 Code LSCAT [22,23] implemented by Y. Namito.
Electrons were not transported and the cutoff energy for photon transport in all calculations was 1 keV (PCUT=0.001MeV). The “importance sampling” technique was used in which photons were not allowed to undergo photoelectric absorption, but were forced to scatter at each interaction site. Photon histories were terminated by Russian roulette if their relative weights fell below a cutoff of 0.05 for water / solid water simulations.

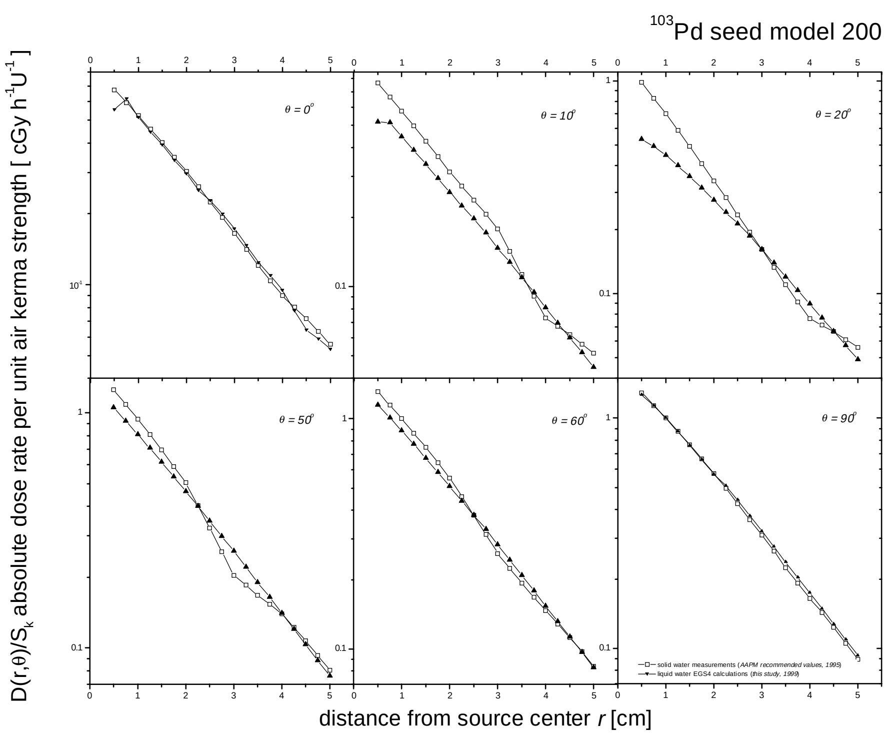

Figure 1. Absolute dose rate distribution for ^{103}Pd seed model 200. EGS4 calculated values are compared with AAPM TG 43 recommended values. All values were calculated following ICWG protocol. Dose rate constant was chosen 0.669 cGy h^{-1} U^{-1} as calculated in [17]

2.3. Brachytherapy sources and phantoms.

For the sources studied the basic sizes and materials of the core and capsules (cladding) used in the calculations were taken as follows: ^{125}I and stainless steel covered ^{192}Ir seeds as described by Williamson [43], Pt covered ^{192}Ir seeds (0.1 mm thick cladding) as described by Nath *et al* [26], ^{103}Pd seed model 200 as described by Chiu-Tsao and Anderson [5], ^{169}Yb model X1267 as described by Piermattei *et al* [32], ^{169}Yb model 5 as described by Mason *et al.* [18] and ^{169}Yb model 8 as described by MacPherson *et al.* [16] (from now on model 8a) and by Das *et al* [8] (from now on model 8b). Energy spectra of source photons are taken from the NUDAT database [BNL 1996]. The composition by weight of solid water was taken from Williamson 1991 and is stated to be hydrogen 8.0%, carbon 67.22%, nitrogen 2.4%, oxygen 19.84%, calcium 2.32%, and chlorine 0.13%. Its density was taken as 1.015 g/cm^3.

3. RESULTS

3.1. Low energy brachytherapy sources.

3.1.1. ^{103}Pd seed model 200

^{103}Pd sources are less studied than ^{125}I and ^{192}Ir sources. Meigooni *et al* 1990 and Chiu-Tsao and Anderson 1991 performed dose measurements using LiF TLD in a solid water phantom. Both results were in good agreement (within 5 %) for distances greater than 2 cm. We compared our

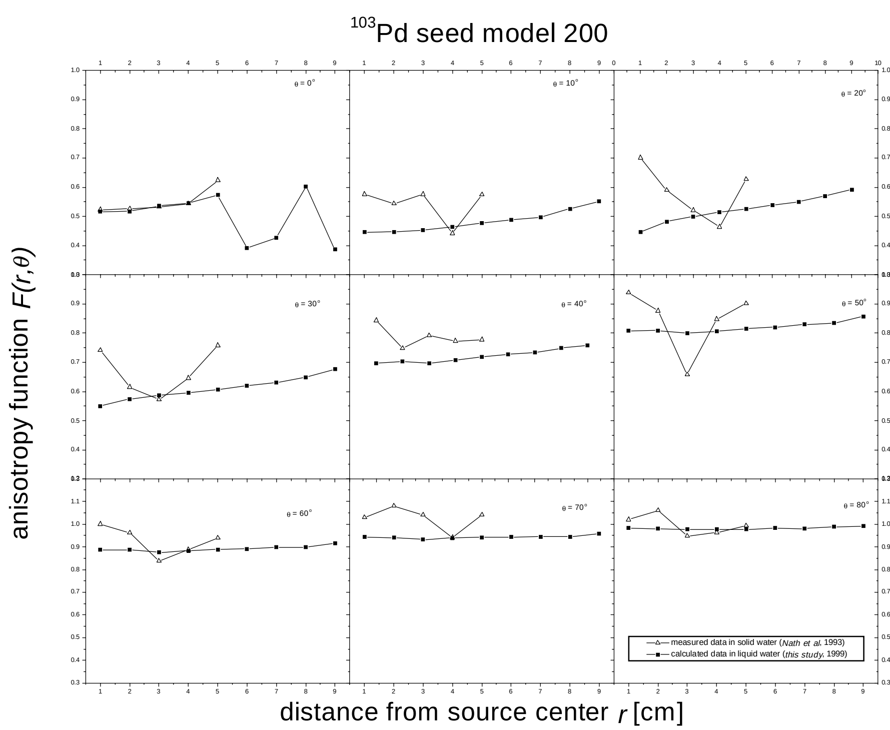

Figure 2. Anisotropy function F(r,θ) comparison between EGS4 calculated data and experimentaly determined values by Nath [Nat *et al.* 1993]

calculated data with the compromise chosen by the AAPM Task Group No.43 [Nath *et al* 1995] of averaging the above mentioned data sets to obtain the radial dose function g(r) and using the anisotropy function $F(r, \theta)$ as measured by Nath [Nath *et al.* 1993]. Absolute dose rate was obtained using a dose rate constant value of 0.669 cGy h^{-1} U^{-1} determined in an early work [17]. Figure 1 shows a comparison between our calculated and AAPM recommended values for absolute dose rate at different angles ranging from the longitudinal to the transverse source axis for ^{103}Pd seed model 200. At 90^o and 0^o the agreement is excellent between liquid water Monte Carlo calculated and measured data. However, there are clear discrepancies with results at angles between the source axis due mainly to statistical fluctuations in the anisotropy function measured by Nath [Nath *et al.* 1993] (see figure 2). Measured values overestimate dose in the clinical significant region close to the source and the longitudinal source axis.

3.1.2. ^{125}I seeds.

Absolute dose rate distributions have been calculated for ^{125}I seed models 6702 and 6711. Figure 3 shows absolute dose rate values calculated by us and AAPM recommended values [Nath *et al* 1995] at different angles ranging from the longitudinal to the transverse source axis for ^{125}I seed model 6702. Calculations in liquid and solid water phantoms together with experimentally measured values are graphically represented. Absolute dose rate was obtained using a dose rate constant value of 0.933 cGy h^{-1} U^{-1} determined in an early work [17]. Results in solid water are consistently smaller than those in liquid water. At 90^o (lower right panel) the agreement is

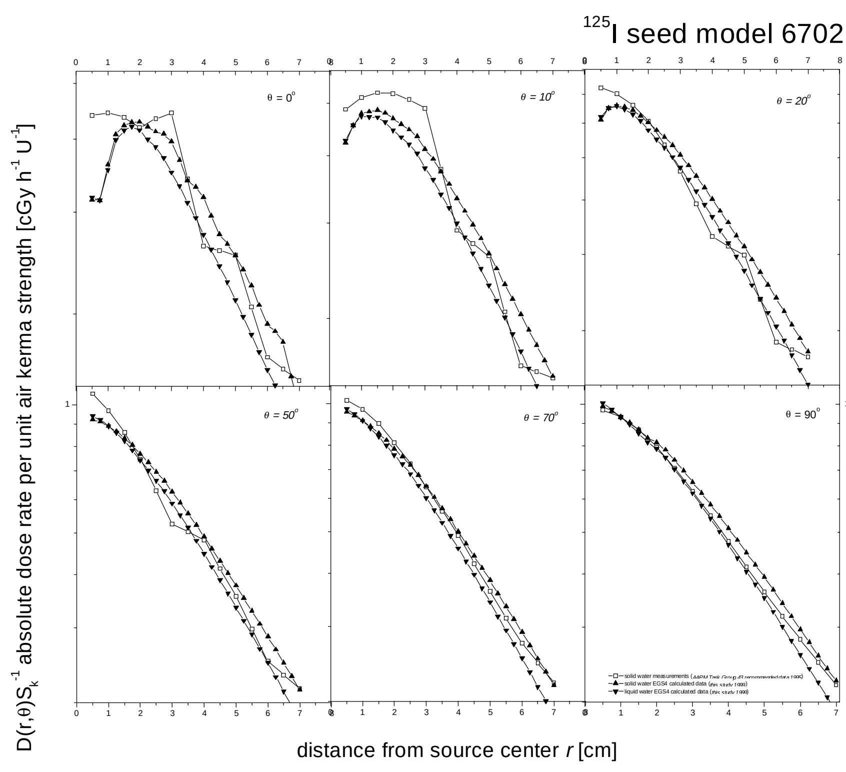

Figure 3. Absolute dose rate values for ^{125}I seed model 6702. EGS4 calculated values are compared with AAPM TG 43 recommended values. All values were calculated following ICWG protocol. Dose rate constant was chosen 0.933 cGy h^{-1} U^{-1} as calculated in [17]

excellent between solid water Monte Carlo calculated and measured data up to 5 cm from source center becoming increasingly worse at clinical irrelevant distances due to artifacts in the ICWG fit of radial dose function to a fifth order polynomial [9]. Approaching the source longitudinal axis at 0^o accuracy gets worse due to photon attenuation and filtration within the source material and the encapsulation end welds. Measured values appear more scattered than Monte Carlo calculated data.

3.2 High energy brachytherapy sources.

3.2.1. ^{192}Ir stainless steel and Pt covered seeds.

Absolute dose rate values for SS and Pt covered seeds were calculated in liquid water under same phantom conditions. Figure 4 shows a comparison with AAPM Task Group 43 recommended

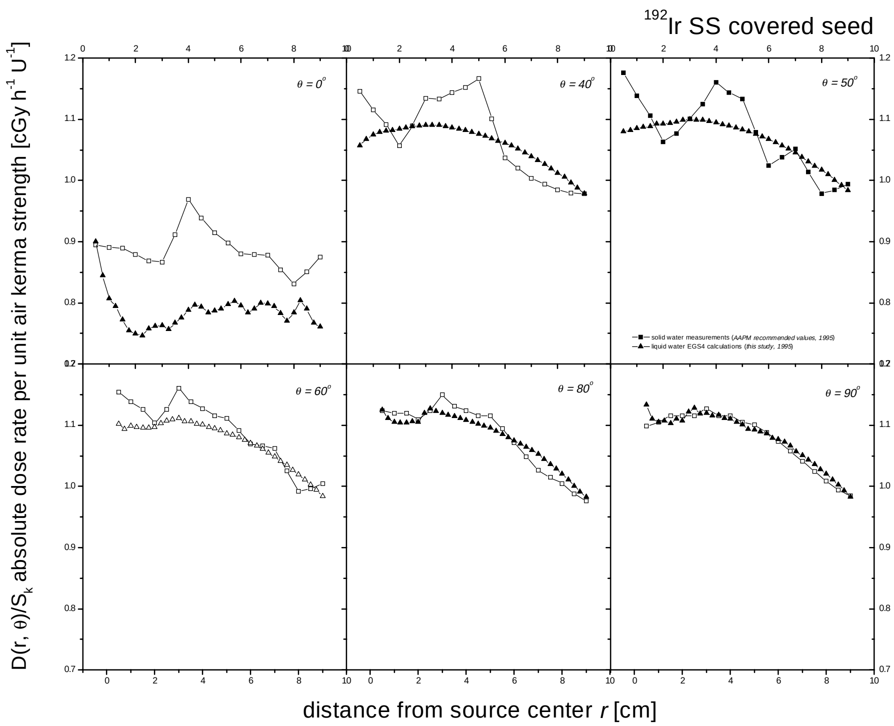

Figure 4. Absolute dose rate per unit air kerma strength for ^{192}Ir stainless steel covered seed. Monte Carlo calculated data are compared to AAPM TG 43 recommended values. Dose rate constant Λ = 1.105 cGy h^{-1} U^{-1} as obtained by us was taken.

values for ^{192}Ir stainless steel at different angles. Absolute values have been obtained using a previously calculated dose rate constant of 1.105 cGy h^{-1} U^{-1} [17]. Excellent agreement is found along the transverse axis becoming increasingly worse towards the longitudinal axis where statistics are poor due to attenuation in the source and the encapsulation. Strong statistical fluctuations are observed in the experimental values.

3.2.1. ^{169}Yb seed model 8b.

Several Monte Carlo results for ^{169}Yb sources have been already published. Although experimental studies have been also performed, there are not experimental dose rate distributions reported in the literature nor have they been recommended. We calculated absolute dose rate distributions in water for ^{169}Yb model X1267, model 5, model 8a after MacPherson *et al.* [16] and model 8b after Das *et al* [8]. Absolute values have been obtained using a previously calculated dose rate constant of 1.204 cGy h^{-1} U^{-1} [8]. Figure 5 compares our calculated absolute dose rate distributions with those calculated by Das *et al.* using MCPT code for model 8b. As can be observed there is an excellent agreement between both calculations excluding the values along the transverse source axis where our results have larger statistical fluctuations.

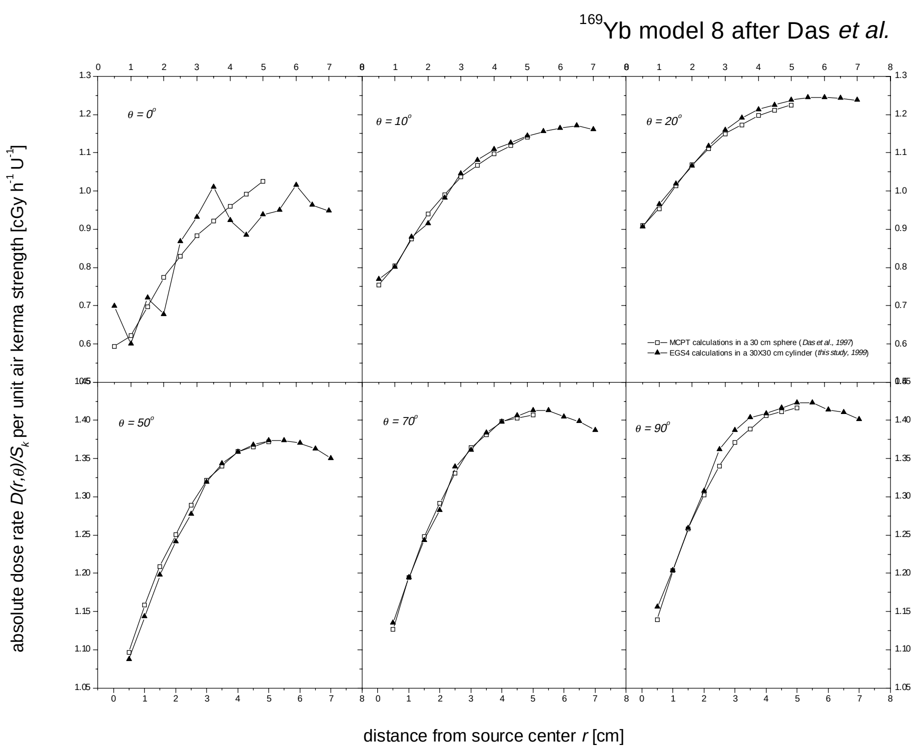

Figure 5. Absolute dose rate per unit air kerma strength for ^{169}Yb seed model 8. EGS4 Monte Carlo calculated data are compared with AAPM TG 43 recommended values. Dose rate constant Λ = 1.204 cGy h^{-1} U^{-1} as obtained by Das *et al.* was taken.

4. DISCUSSION

Calculation of 2D absolute dose rate distributions about several brachytherapy sources has been undertaken. Results have been compared with recommended values for clinical use. Under certain conditions, the accuracy of dose calculations with Monte Carlo simulation of photon transport rivals that of the best experimental measurements available. At present time there aren't codes available sufficiently fast to support patient specific treatment planning although some efforts are being already made in the United States to achieve it under the project name PEREGRINE. However, Monte Carlo simulation functions well as a quality assurance or dosimetry aid supplementary and analogous to dose measurement.

Accuracy of Monte Carlo calculations can be unlimited improved providing better estimators and more powerful computers are used. Experimentally verified Monte Carlo simulation of photon transport is a powerful clinical dosimetry tool providing artifact free dose rate distributions about clinically relevant combinations of sources and applicators.

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REFERENCES

1. **Bielajew A F and Rogers D W O 1989,** *DOSRZ user code, EGS4 distribution package*
2. **Brookhaven National Laboratory 1996,** NUDAT database, last update 01/31/96**,** National Nuclear Data Center, Upton, N.Y., USA
3. **Burns G S and Raeside D E 1988,** "Two-dimensional dose distribution around a commercial ^{125}I seed", *Med.Phys.* ***15*** *56-60*
4. **Chiu-Tsao S T, Anderson L L, O'Brien K and Sanna R 1990, "**Dose rate determination for I-125 seeds", *Med. Phys.* ***17*** *817-825*
5. **Chiu-Tsao S T and Anderson L L 1991, "**Thermoluminiscent dosimetry for Pd-103 (mod.200) in solid water phantom", *Med. Phys.* ***18*** *449-452*
6. **Dale R G 1983,** "Some theoretical derivations relating to the tissue dosimetry of brachytherapy nuclides, with particular reference to ^{125}I", *Med. Phys.* ***10*** *176-183*
7. **Dale R G 1986,** "Revisions to radial dose functions data for ^{125}I and ^{137}Cs ", *letter to Med. Phys.* ***13*** *963-964*
8. **Das R K, Meigooni A S, Mishra V, Langton M A and Williamson J F 1997, "**Dosimetric characteristics of the Type 8 Ytterbium-169 instertitial brachytherapy source", *J.Brachytherapy Int'l* **13**, p.1
9. **Interstitial Collaborative Working Group (ICWG) 1990**, "*Interstitial Brachytherapy: Physical, Biological, and Clinical Considerations"*, ed. L.L. Anderson, R. Nath and K.A. Weaver (Raven, New York), p.21-32

10. **Herbolt G, Hartmann G, Treuer H and Lorenz W J 1988**, "Monte Carlo calculation of energy buildup factors in the range from 15 to 100 keV with special references to the dosimetry of ^{125}I seeds", *Phys.Med.Biol. 33 1037-1053*
11. **Leliveld C J, Maas J G, Bom V R and Van Eijk C W E 1995**, *presented at the IEEE Medical Imaging Conference, October 26-28, San Francisco, 1995*
12. **Ling C C, Schell M C and Yorke E D 1985**, "Two-dimensional dose distribution of ^{125}I seeds", *Med. Phys.* ***12*** *652-655*
13. **Loftus T P 1984, "**Exposure standartization of iodine-125 seeds used for brachytherapy", *J. Res. Natl. Bur. Stand.* ***89*** *295-303*
14. **Luxton G, Astrahan M A, Findley D O and Petrovich Z 1990, "**Measurement of dose-rate from exposure calibrated I-125 seeds", *Int.J.Radiat.Oncol.Phys.* ***18*** *1199-1207*
15. **Luxton G 1994, "**Comparison of radiation dosimetry in water and in solid phantom materials for I-125 and Pd-103 brachytherapy sources: EGS4 Monte Carlo study", *Med. Phys.* ***21*** *631-641*
16. **MacPherson M S and Battista J J 1995, "**Dose distribution and dose rate constant for new ytterbium-169 brachytherapy seeds ", *Med. Phys.* ***22*** *89-96*
17. **Mainegra E., Capote R. López E 1998**, "Evaluation of dose rate constant for Pd-103, Ir-192, Yb-169 and I-125 brachitherapy sources: An EGS4 Monte Carlo study", *Phys.Med.Bio.* ***43*** *1557-1566*
18. **Mason D L D, Battista J J, Barnett R B and Porter A T 1992, "**Ytterbium-169: Calculated physical properties of a new radiation source for brachytherapy", *Med. Phys.* ***19*** *695-703*
19. **Meli J A, Meigooni A S and Nath R 1988, "**On the choice of phantom material for dosimetry of Ir-192 sources", *Int. J. Radiat. Oncol. Biol. Phys.* ***14*** *587-594*
20. **Meigooni A S, Sabnis S and Nath R 1990, "**Dosimetry of palladium-103 brachytherapy sources for permanent implants", *Endocurietherapy Hypertherm. Oncol.* ***6*** *107-117*
21. **Morin L R M 1982**, "Molecular form factors and photon coherent scattering cross section of water", *J. Phys. Chem. Ref. Data.* ***11*** *1091-1098*
22. **Namito Y, Ban S and Hirayama H 1994**, "Implementation of Doppler broadening of Compton scattered photon into the EGS4 code", *Nucl.Instr.and Meth.* ***A349****, 489-494*
23. **Namito Y, Ban S and Hirayama H 1995**, "LSCAT:Low-energy photon scattering expansion for the EGS4 code", *KEK Internal Report 95-10,* National Institute for High Energy Physics, Japan
24. **Nath R, Meigooni A S and Meli J A 1990,** "Dosimetry on transverse axes of I-125 and Ir-192 instertitial brachytherapy sources", *Med. Phys.* ***17*** *1032-1040*
25. **Nath R, Meigooni A S, Muench P and Melillo A 1993,** "Anisotropy functions for ^{103}Pd, ^{125}I and ^{192}Ir instertitial brachytherapy sources", *Med. Phys.* ***20*** 1465-1473
26. **Nath R, Anderson L L, Luxton G, Weaver K A, Williamson J F, Meigooni A S 1995,** "Dosimetry of instertitial brachytherapy sources: Recommendations of the AAPM Radiation Therapy Committee Task Group 43", *Med. Phys.* ***22*** *209-234*
27. **Nelson W R, Hirayama A and Rogers D W O 1985**, "*The EGS4 code system,Version 4*", *Stanford Linear Accelerator Center Report SLAC-265,* Stanford, USA
28. **Nelson W R and Rogers D W O 1988 "***Monte Carlo transport of electrons and photons*", ed. T.M.Jenkins, W.R.Nelson and A.Rindi (Plenum, New York) *pp.287-306*

29. **Perera H, Williamson J F, Zuofeng Li, Mishra V and Meigooni A S 1994, "**Dosimetric characteristics, air kerma strength calibration and verification of Monte Carlo simulation for a new ytterbium-169 brachytherapy source", *Int. J. Radiat. Oncol. Biol. Phys.* ***28*** *953-970*
30. **Piermattei A, Arcovito G and Andreasi Bassi F 1988, "**Experimental dosimetry of I-125 new seeds(mod.6711) for brachytherapy treatments", *Phys. Med.* ***1*** *59-70*
31. **Piermattei A, Arcovito G , Azario L, Rossi G, Soriani A and Montemaggi A 1992, "**Experimental dosimetry of Yb-169 prototype 6 for brachytherapy treatments", *Phys. Med.* ***8*** *163-169*
32. **Piermattei A, Azario L, Rossi G, Soriani A,Arcovito G,Ragona R, Galelli M and Taccini G 1995, "**Dosimetry of Yb-169 seed model X1267", *Phys.Med.Biol.* ***40*** *1317-1330*
33. **RSIC 1993**, *RSIC Data Package DLC-136/PHOTOX*, "Photon Interaction Cross Section Library" contributed by National Institute of Standards and Technology.
34. **Sakamoto Y. 1993**, *Proc. Third EGS4 User's Meeting in Japan, KEK Proceedings 93-15, National Institute of High Energy Physics, Japan*
35. **Scarbrough E C, Sanborn G E, Anderson J A, Nguyen P D, Niederkorn J Y and Antich P P 1990**, "Dose distribution around a 3.0-mm type 6702 I-125 seed", *Med.Phys.* ***17*** *460-463*
36. **Schell M C, Ling C C, Gromadzki Z C and Working K R 1987**, "Dose distributions of model 6702 I-125 seeds in water", *Int.J.Radiation Oncology.Biol.Phys.* ***13*** *795-799*
37. **Thomason C and Higgins P 1989,** "Radial dose distribution of Ir-192 and Cs-137 seed sources", *Med. Phys.* ***16*** *254-257*
38. **Wang R and Slovoda R 1996, "**EGS4 dosimetry calculations for cylindrically symmetric brachytherapy sources", *Med. Phys.* ***23*** *1459-1465*
39. **Weaver K A, Smith V, Huang D, Barnett C, Schell M C and Ling C C 1989, "**Dose parameters of I-125 and Ir-192 seed sources", *Med. Phys.* ***16*** *636-643*
40. **Williamson J F, Deibel F C and Morin R L 1984,** "The significance of electron-binding corrections in MC photon transport calculations"**,** *Phys.Med.Biol.* ***29*** *1063*
41. **Williamson J F 1988, "**Monte Carlo evaluation of specific dose constant in water for I-125 seeds", *Med. Phys.* ***15*** *686-694*
42. **Williamson J F and Nath R 1991, "**Clinical implementation of AAPM task group 32 recommendations on brachytherapy source strength specification", *Med. Phys.* ***18*** *439-448*
43. **Williamson J F 1991, "**Comparison of measured and calculated dose rates in water near I-125 and Ir-192 seeds", *Med. Phys.* ***18*** *776-786*
44. **Williamson J F 1995** *As stated in TG43 Report* [Nath *et al* 1995], *page 215*