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Program Development for Dose Distribution of Curved Sources Configuration of ^{60}Co Based On Superposition Method and Egsnrc Code

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ABSTRACT

Introduction: Brachytherapy uses a treatment planning system (TPS) based on the American Association of Physicists in Medicine Task Group-43 formalism for cylindrical sources. The precise calculation of the dose distribution for particles transported through different media depends on the appropriate choice of Monte Carlo components (the spectral energy of photons and electrons, the nature of the medium, the interaction process, the transport algorithm).

Material and Methods: In the present work, we first used the Monte Carlo user code DOSRZnrc to simulate the dose distribution in a cylindrical water medium. Some programs used in Brachytherapy are based on TG43 database of cylindrical sources and correct for photon attenuation and scatter effects associated with the Titanium applicator or catheter. This work is composed of two phases: the first is the simulation of the ^{60}Co seed source attached to a stainless steel cable of 9.8mm and injected into plastic and Titanium Applicator or Catheter matarials with 14.75mm of length, its a complete simulation to avoid correction factors for photon attenuation and scatter, and providing the program with greater flexibility will occupying less memory. In The second phase, a program is developed to calculate the dose distribution of the ^{60}Co seed sources injected into a Titanium applicators or catheter for linear and curved configurations using the superposition method with the user-supplied database from the user code DOSRZnrc by summing all doses from each step of the seed source in its path on the applicator.

Results: The program developed herein is compared with the TPS Sagiplanalgorithm and good agreements were found with the results of dose distribution: 90% of the points on the calculation matrix have a relative deviation of 1-5% which in general are situated far enough from the Applicator (over 2mm); 8% of these points have 6-10% and 2% have 10-14% from which these later points are a bit near the Applicator(1-2mm). The program can calculate the dose deposited with different adjacent combined configurations on different planes, and an option to choose voxel size: 2mm, 1mm, 0.5mm and 0.2mm in the calculation matrix.

Conclusion: The methodology of this work is the superposition technique, a mathematical tool based on data presimulated by the user code DOSRZnrc of the dose distribution of a ^{60}Co seed source in a simulation matrix. The seed source is injected into a Titanium applicator or catheter for a curved/linear configuration, and the superposition program calculates the dose distribution in a calculation matrix. This work was compared with the Sagiplan algorithm, and good agreement was obtained. In the future, we aim to to include the heterogeneity effect and Cartesian geometry to cover more complex cases.

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Introduction

In contrast, in External Beam radiotherapy (EBRT) where the dose is delivered from an external beam of photons, electrons or heavy particles at a along distance from the source, in Brachytherapy (BT) the objective is to deliver a dose into or in contact with the tumour with the use of a seed source injected in flexible or rigid applicators with different curved or linear configurations, so the aim to reduce dose to organ at risk will be achieved [1,2]. In teletherapy, the dose distribution is homogeneous in most cases, whereas in BT, the dose distribution is inhomogeneous, governed by the divergence effect of the field around the seed source and attenuation/scatter far away. The integration of Brachytherapy with External beam therapy is possible in some cases and is related to mathematical models of radiobiological effects, because these effects differ between high-dose-rate EBRT and high-dose-rate BT.

There are different treatment modalities with the seed source. When the dose is delivered at a low dose rate (LDR), reperfusion of sublethal tissues is more effective than that of malignant tissues. As the dose rate increases (HDR), there is less time for such repairs to occur. The repair of sublethal damage can be further enhanced by dose fractionation; therefore, the total dose in HDR modality must be reduced

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relative to LDR modality to achieve an equivalent biological effect.

The calculation and prescription of a dose in Radiotherapy and Brachytherapy require detailed information on the beam characterization, the radioactive source, and the physics of the transport media. It's a goal that remains governed by the Monte Carlo technique because of current knowledge of the scattering and absorption cross-section of radiation with matter, the physics of media, and the algorithms developed.

Before being used clinically, sources should be measured using one of two methods: a well chamber or an in-air air kerma measurement with an ionisation chamber. the latter requires correction factors for distance from the source chamber and chamber size, which should be calibrated in a standard laboratory.

In Brachytherapy, the direct measurement of dose distribution in regions near the radioactive source and medium interfaces is impossible because of the high dose gradient in these regions [3,4] which is of the orders of the size of a dosimeter. For this reason, different methods have been developed to solve this problem: a model of line source given by Meisberger and Sakilliou [5,6] ignores attenuation and scattering in medium, the superposition method which is a mathematical tool in radiotherapy for dose distribution in patients with heterogeneous media, this method can be reduced to the convolution method in the case of homogenous medium, the convolution method is frequently resolved by the Fast Fourier Transform (FFT) [7-11].

The Task Group TG43 of the AAPM Radiation Therapy Committee has published recommendations on dosimetry formalism and dosimetry parameters for Interstitial Brachytherapy sources. It was primarily considered for low dose rates and now is widely used for HDR and PDR of ^{60}Co and ^{192}Ir seed sources. The TG43 incorporated the dose rate constant and several dosimetric parameters that depend on the source design and can be extracted from measurements or MC simulation in a water medium.

In this study the superposition method was used to map a complete dose distribution in water of a ^{60}Co seed source of high dose rate, injected into a Titanium applicator or Catheter with linear and curved configurations at different angles and radii. The database used as input to generate the dose for the curved/linear sources is a simulation of dose distribution with the user code DOSRZnrc, This input is a direct simulation of ^{60}Co seed source attached to stainless steel cable of 9.8 mm and injected in a Titanium Applicator or Catheter to avoid correction factors for photon scatter and attenuation, and yield flexibility to the program and less memory occupied. It is a method proposed to calculate the dose distribution for a group of adjacent sources of different curved and linear forms, sited in plans of constant detachments. Good agreement was found in the dose distribution of curved forms, such as Vaginal and Uterine Applicators, and other forms for Catheter between the Sagiplan platform and this work.

One of the challenges encountered in this work is the limited number of concentric cylinders in the simulation geometry of the user code DOSRZnrc. The greatest number in the cylinder, the greatest flexibility in program calculation, and good fitting between voxels in the calculation matrix. The maximum number of cylinders was set to 100, which is inadequate for good spatial resolution, After reviewing different script files in the EGSnrc code, we have decided to increase this number up to 1000 cylinders.

In this study, the heterogeneity issue in the dose calculation was not addressed, We have adopted the approach of the majority of software, that uses water as a reference medium for dose calculation in biological tissues, and it is sufficient for the majority of sources (height and medium energy) encountered in BT treatment. Furthermore, in this study, the different spatial orientation of the different curved/linear configuration sources is limited to adjacent sources (axial sources are parallels or oriented at 90° to each other). Up to five sources planes and twenty calculation planes with constant increment to calculate the dose distribution for adjacent and superimposed sources for different curved/linear configuration sources.

Materials and Methods

Code EGSnrc

The most clinically applicable methods for the dose calculation require detailed information on the characterization of the beam (spatial and energetic distributions of photons and electrons) and the physics of the transport media. It's a goal that remains governed by the Monte Carlo technique because of current knowledge of the physical laws, the scattering and absorption cross-sections of radiation with matter, the physics of media, and the developed algorithms and statistical methods for the treatment results for different physical quantities of interest. Advances in computing machines and processors have motivated several major treatments planning system vendors to adopt Monte Carlo techniques [12-16].

The code Monte Carlo used for this work is: The Electron Gamma Shower (EGS) was developed by the National Research Council of Canada, the EGSnrc is a coupled code that simulates the transport of photons and electrons for which the energy varied from around ten keV to 1GeV and had an arbitrary geometry (spherical, cylindrical and cartesian) with different media (all chemical elements on different physical states and 330 compounds) [17-20].

User code

The EGSnrc system is composed of many user codes, DOSRZnrc and FLURZnrc to simulate the

transport of photons and electrons and calculate different physical quantities (dose, fluence spectra,..) in cylindrical geometry with twenty different source configurations. DOSXYZnrc to score the dose in Cartesian geometry, EDKnrc to generate an Energy Deposition kernel for photons and electrons forced to interact in the center of the sphere, and CAVRZnrc calculates various factors of interest when using cavity ionization chambers, stopping power ratio, and another user code. To calculate the dose distribution around a ^{60}Co seed source, we have used the user code DOSRZnrc [21] with cylindrical geometry to simulate the transport of electrons and photons. The photons are emitted from a seed source situated at the centre of the cylinder. The voxels in which the dose distribution is simulated are composed of concentrically arranged cylinders crossed by some planes or slabs. We can associate different material sizes with this ring voxel. We have summarized in Appendix A1 the different input values and Monte Carlo transport parameters to run a simulation.

Seed source

The dose distribution simulated with the user code DOSRZnrc was calculated from photons with a mean energy

of 1.25 MeV (according to the photon spectrum of ^{60}Co: 1.1732 and 1.3325 MeV with roughly the same intensity). The unit of dose is Gy/photon. The photons are emitted randomly in different directions and path interactions, and the choice of medium is water-equivalent biological tissue material. In this work, the seed source simulated is

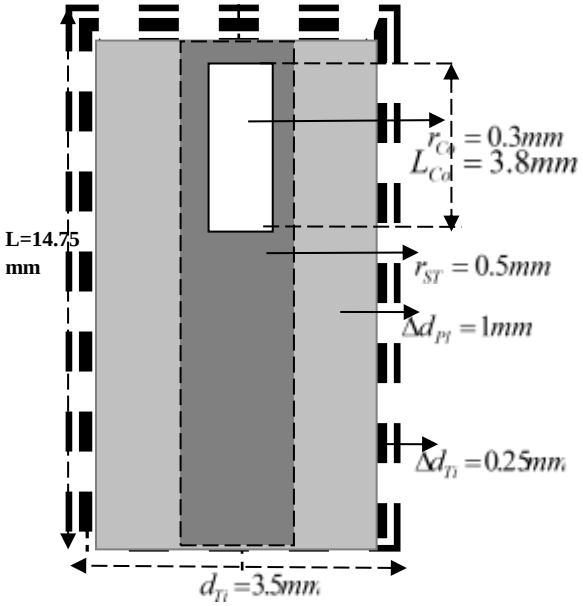


Figure 1.The geometry of the seed source injected in Titanium and plastic materials.

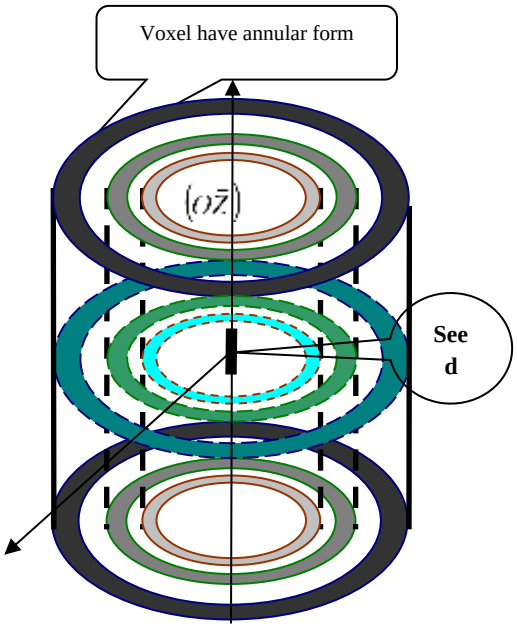


Figure 2: The geometry used in the simulation of the dose distribution for a ^{60}Co seed source in water medium.

the HDR ^{60}Co, while the size of the ^{60}Co seed source is 0.6 mm of active core diameter and 3.8 mm long cylinder, with the radioactive material uniformly distributed. Around this core is stainless steel type 3161 capsule with an outer diameter of 1 mm and a 4.2 mm long cylinder. The material is composed of Si (0.7%), Mg (17%), Mn (1%), Fe (66.8%), Ni (12%), and Mo (2.5%) [22].This material defined the wall of the seed source with a 0.2 mm thickness to retain the radioactive material in the source. The radioactive source is attached to a 9.8 mm long cylinderthat severs as the source cable. In reality, this cable is 1 to 2 m long; however, the 9.8 mm long cylinder made with stainless steel material is sufficient to take into account the attenuation of photons emitted by the source itself on the source axes, a ratio of 10^{-3} between the dose calculated in the longitudinal axes and transverse axes of the source was found. Two simulation configurations are made: The first one, the seed source is injected into a Catheter (plastic material) with a 1 mm thickness and an outer diameter of 3 mm, and a long cylinder measuring 14 mm. The second one with the previously defined geometry configuration injected into an applicator of Titanium material with a thickness of 0.25 mm and an outer diameter and cylinder length of 3.5 and 14.25 mm, respectively. We have illustrated in Figure 1 the seed source's geometry and the corresponding Titanium Applicators. Appendix figure A2 demonstrates the disintegration mode for $^{60}_{27}Co$ isotope.

Geometry of Simulation

For the first time, the cylindrical geometry is composed of 415 plans and 100 concentric cylinders by default, with different radii: from the first to the 70th cylinder, the thickness is 0.7 mm; from the 71st to the

93rd, 2 mm, and 12 mm for the rest. The cylinders are traversed by adjacent plans with a fixed thickness of 0.7 mm. Figure 2 illustrates a schematic of the geometry used to simulate the dose of the seed source. First, this geometry was selected because of the limited number of cylinders. After reviewing the different script files of the code EGSnrc, the number of cylinders was increased (possibly up to 1000). The geometry was fixed to 750 cylinders and 1500 planes, all with the same thickness of 0.2 mm. The program's calculation time is long enough for the first geometry, but it certainly occupies less memory; however, the current geometry $\Delta r \ and \ \Delta z = 0.2mm$ was chosen, which provides good flexibility for the program.

Superposition method

The superposition method is a mathematical tool used across various areas of physical science (signal processing, heat transfer, plasma media). There are several applications of its in radiotherapy: the dose distribution in patients for high energy photon fields on heterogeneous media, and the Clarkson integration method for dose calculation in irregular photon fields.

In Brachytherapy, Boyer and Edward implemented the convolution and superposition methods for some seed sources to calculate dose distribution using a Fourier transform-based approach across a calculation matrix. Other works have been investigated by Jeffrey F. Williamson, who developed a dose computational algorithm sufficiently fast for clinical use based on the convolution/superposition methods to compute the dose distribution in a heterogeneous medium. In many cases, the convolution/superposition algorithms are frequently resolved by the Fast Fourier Transform (FFT) [7-11, 23].

In this work the dose calculation relies on two distinct phases to ensure both accuracy and computational efficiency:

In the first phase, a static 3D dose distribution (dose kernel) is pre-calculated for a single stationary ^{60}Co seed source using the DOSRZnrc Monte Carlo code. This phase accurately simulates all photon and electron transport events, including kinetic energy deposition via the Class II model of the electron transport algorithm. this first phase give a simulation matrix data.

In the Second phase, the custom superposition program performs a pure geometric translation of this pre-calculated static data along the successive steps of the Applicator or Catheter path. Therefore, no active Monte Carlo simulation occurs during the rapid spatial translation phase, this later give a calculation matrix. Generally, the calculation matrix has a size of 15 cm by 20 cm, the data input supplied by the user code DOSRZnrc is a direct simulation of ^{60}Co seed source attached to stainless steel cable and injected in a Titanium Applicator or Catheter (sees figure 1) to avoid correction factors for photons scatter and attenuation on the applicators and yield flexibility to the calculation program, with less memory occupied, furthermore a good spatial resolution on dose distribution is needed for a good prescribed dose and dose volume hectogram (DVH), this goal is achieved by reducing the size of the voxels (up to 0.2 - 0.5 mm on the simulation matrix) which reflects to a great number of planes and concentric cylinders (as discussed in the Source and Geometry sections). Figure 3 illustrates a curved source configuration, where all geometric parameters correspond to the indices of the simulation and calculation matrices. For each point *P*(x,y,z), the dose distribution represents the cumulative contribution from each step of the ^{60}Co seed source along the path of the applicator or catheter for both curved and linear configurations. The displacement of the seed begins in the upward direction from a polar angle for the curved portion, and in the downward direction for the linear portion (as illustrated in the figure).

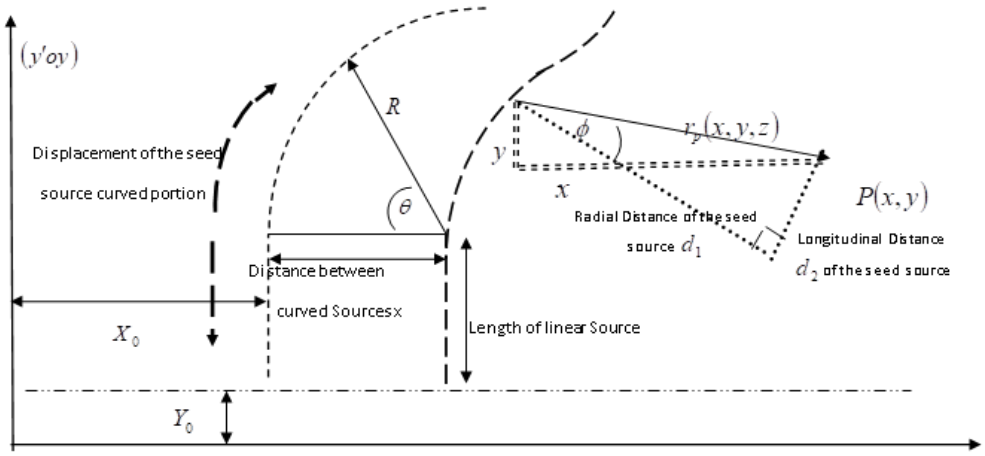


Figure 3. The assembled geometric parameters for a curve and linear configuration source. All distances are given in mm units.

The distances and geometric parameters $(R\ X_0\ Y_0.....)$ are given in mm units, and their choices are arbitrary; the dose calculated in the calculation matrix is related to several parameters, citing some of them:

d_1 and d_2 is the perpendicular and parallel distance to the axial source, respectively given by:

$$\begin{cases} d_1(x,y,z) = \cos(\phi).r_p(x,y,z) \\ d_2(x,y,z) = \sin(\phi).r_p(x,y,z) \end{cases} \quad (1)$$

These two are calculated using the indices (i,j) and parameters (a,b) used in the simulation matrix, along with other geometric parameters in the calculation matrix. It must be mentioned that the system coordinates (x,y,z) are replaced by the indices (i,j,h) in the program.

The dose at each point (i,j,h) on the grid matrix is the accumulation or superposition of the dose from all seed sources steps on the applicator or catheter.

The total dose at the point (i,j,h) of the calculation matrix for a given linear or curved configuration source is given by:

$$D(i,j,h,s) = 2\times \sum_{k=1}^{k\max} d(i',j',h,k)*\Delta t(k,s)*A(s) \quad (2)$$

The indices i' and j' signified the plane and the cylinder number of the simulation matrix; these indices are according to the geometry parameters, with indices i and j which define the number of rows and columns in the calculation matrix in the program of the superposition method, the summation $\sum_{k=1}^{K\max}$ is given with the total number of the seed source steps.

- h *and* s are the number of planes and curved/linear configuration sources respectively.

- $d(i',j',h,k)$ is the value of dose by photon for the (k^{th}) step of the seed source on the Titanium Applicator or Catheter calculated by the user code DOSRZnrc in the simulation matrix.

- $D(i,j,h,s)$ is the dose by photon calculated from the contribution of all steps of the seed source.

- $\Delta t(k,s)$ is the treatment time for the k^{th} stepseed source and s^{th} linear/curved source. Where $A(t)$ is the activity of the ^{60}Co seed sources, and the factor 2 in the formula (2) is introduced because we have two photons produced by one disintegration .

In accordance with the precedent equations, the total dose D_G for a group of planes (h') (generally we have $1\le h'\le 5$) where each plane (h') is occupied with adjacent curved/linear configuration sources, given by:

$$D_G(i,j,h) = \sum_{h'=1}^{h\max s\max} \sum_{s=1} D(i,j,h',s) \quad (3)$$

This work was compared with Sagiplan TPS software; the TPS verification and Commissioning in the BT treatment modality are simpler than the EBRT modality, which leads to different procedures for the description of external beam characteristics in terms of phase space and energeticspectral compared with data supplied for the source radioactive characteristics in BT.[24]. The commissioning and quality assurance program for HDR source has been recommended as a requirement before initiating a patient treatment program to assure the accuracy of the treatment plan. There are some concepts to be verified: dose calculation points, dose volume hestogram, dose homogeneity indices, and others [25,26]. The Sagiplan software is compliant with TG43 protocol, and High Energy Brachytherapy Dosimetry (HEBD), and produces dose calculation for $^{60}_{27}Co$ *and* $^{192}_{77}Ir$ Seed sources injected in Applicators, which takes into account attenuation and shielding with connectivity of different Image modalities (DICOM, IMR , etc) [27].

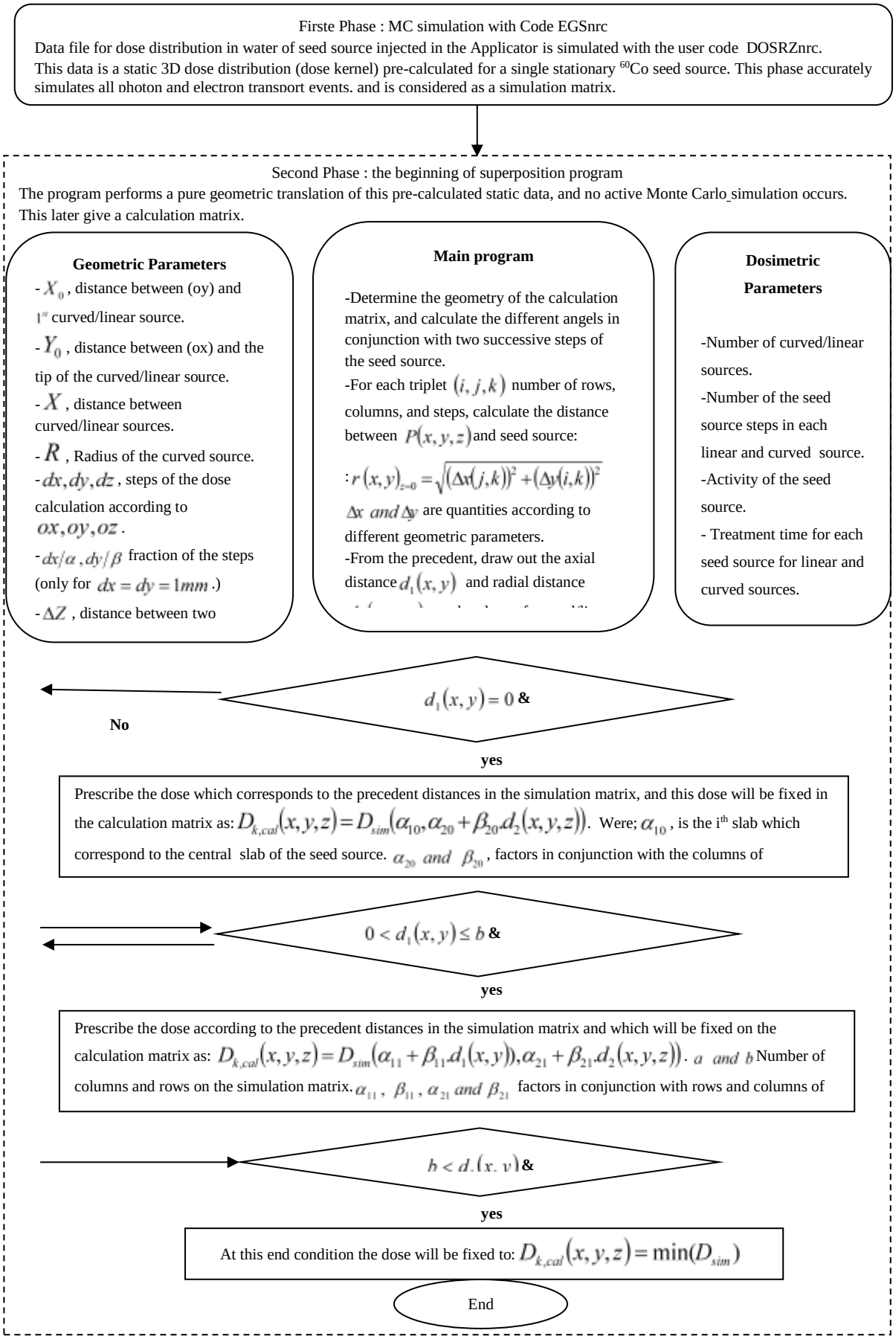


Figure 4. Diagram sums up all the steps of superposition method used in thiswork

Some applicators or catheters do not have a homogeneous curve form; rather, they are composed of two distinct homogeneous segments, each with its own specific radius and opening angle. To address this, the program calculates the total dose distribution of the non-homogeneous applicator by summing the two separate matrix calculations generated for the homogeneous ones, and all geometric and dosimetric parameters are determines manually within the GUI. Consequently, the junction between these two segments of homogeneous applicator are determine by the algorithm, This two calculation matrix are describes as follow: If a oesophageal or bronchus configuration is requested, the first matrix is considered as the basic matrix and no mathematical transformation is made. Will, the second matrix is inverted left/right or up/down, and must have the same matrix size as the first one and keep/retain the rest of the same geometric and dosimetric parameters as the non homogeneous applicator.

There are four Graphical User Interfaces, roughly with the same forms and composition of objects. Related to script file building and writing in the MATLAB technical language. In A8 the graphical user interface of the program is shown, including all geometric and dosimetric parameters.

Results

Attenuation effects and the Curved isodose of the seed source

In Figures 5 and 6, the isodose curve around a seed source for the two geometries is illustrated; the smoothness of the curve in Figure 6, in contrast to Figure 5, is notable given the small voxel size, which agrees with the good fit of curves. The curves are isodose curves from direct simulation for HDR ^{60}Co seed sources and a large number of photons $N \approx 6*10^{8}$ (number of history in statistical terms) with uncertainty $\sigma = \pm 10\%$ near the longitudinal axis. These uncertainties are illustrated in Figure 12, increasing in regions near the longitudinal axis of the source and becoming smaller $(\sigma < 1\%)$ near the transverse axis. With the use of the program based on the superposition method, the contribution of the number of seed sources (number of

of a curved source configuration is between two and five minutes, where as with the direct Monte Carlo simulation, it's tens of hours for a linear configuration source with the user code DOSRZnrc.

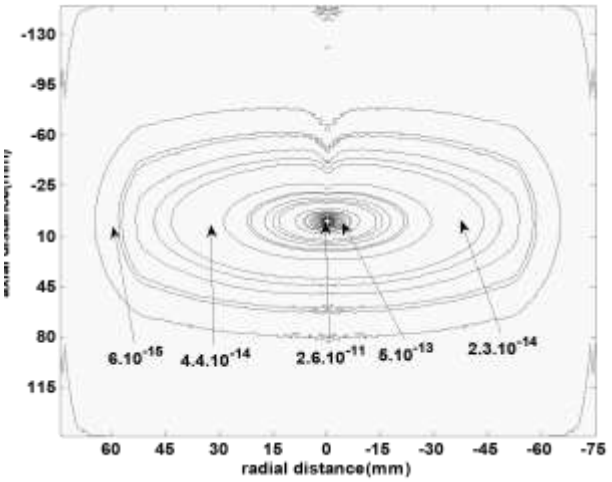


Figure 5. Dose distribution of the HDRCo^{60} seed source according to the first geometry.

Comparison between the Sagiplan platform and this work

The dose distribution calculated by the Sagiplan algorithm platform [28] used in oncology treatment for seed sources in Brachytherapy and this work has been compared. The algorithm is based on the data provided by the dosimetry protocol AAPM TG43 [29-33], uses water as the reference medium for the dose calculation. Figure 7 (a and b) shows the gamma Index for three curved sources configurations with: uterine applicator situated midway between two vaginal applicators distances 15mm from each other.

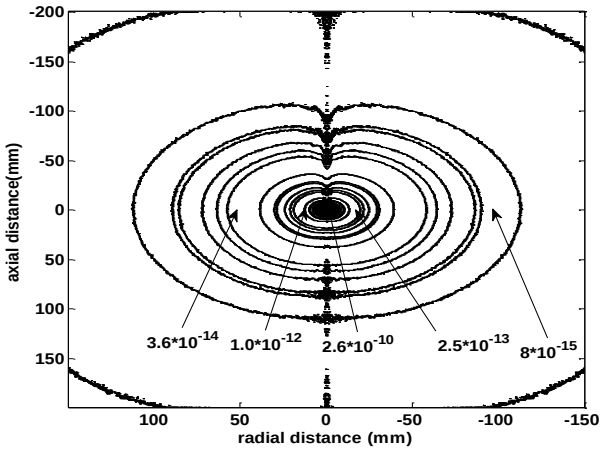
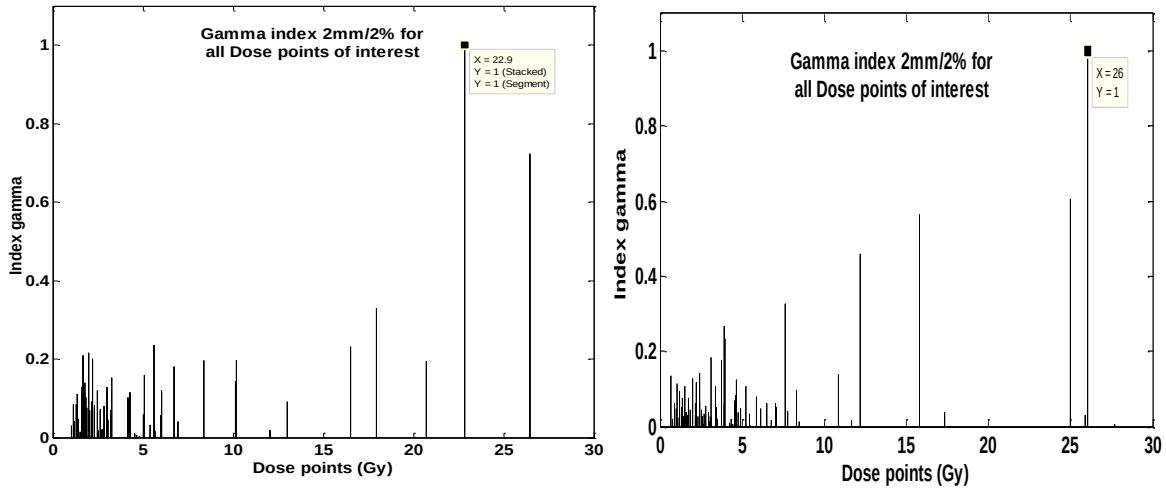


Figure 6. Dose distribution of a HDRCo60 seed source according to the second geometry All curve have the same appearance.



(a) (b)

Figure7. Gamma index for three curved sources configurationaccording to dose points. -7-a- in vaginal applicators plans. -7-b- in the uterine applicators plans. The treatments time by seed step is variable (as expline in the text)

For each reference dose points, the relative deviation is less than or equal to 2% around the dose points in 2mm, and all dose points in the applicators are eliminated. We have traced these curves of the gamma index according to dose points for two calculations plans: in the vaginal applicators and uterine applicators, with variable treatments time for each seed steps (as explained in the next section). We show in Figure 8b the dose distribution calculated by Sagiplan; the square is $1cm \times 1cm$ and the red points are the steps of the seed source in the Applicators. Figure 8c illustrates the dose distribution calculated by this work, and the step for the calculation matrix (dx, dy) is 1 mm.

We give the comparison between the two methods for three curved sources used in the application of intracavitary implant treatment (vaginal and uterine implants). The uterine applicator has a radius of 11.7 cm with an opening angle of 30° situated midway between the two vaginal applicators, this latter has a radius 1.2 cm in the first portion and 11.2 cm in the second one, with a total opening angle of 90°. The distance between each applicator is 1.5 cm. Figure 9 shows the isodose curves for a configuration of three curved sources superimposed: one uterine applicator in the centre, and two vaginal applicators in the extremes.

Two dose distribution have been calculated for each plane (uterine and vaginal).In the first calculation for the Vaginal applicator, the treatment time per step varied, with 7 steps of the seed source: from 5s to 35s with $\Delta t = 5s$ (step on time). For the Uterine applicator, the treatment time varied from 60s to 5s with 12 steps of the seed source. Well on the other calculation, the time of treatment by step is fixed: 20s for the Uterine Applicator and 10s for the vaginal one. A good balance has been found between the two methods. Here, we present the relative deviation in the dose distribution calculated using the two methods for the second calculation (fixed treatment time, see Figure 9).

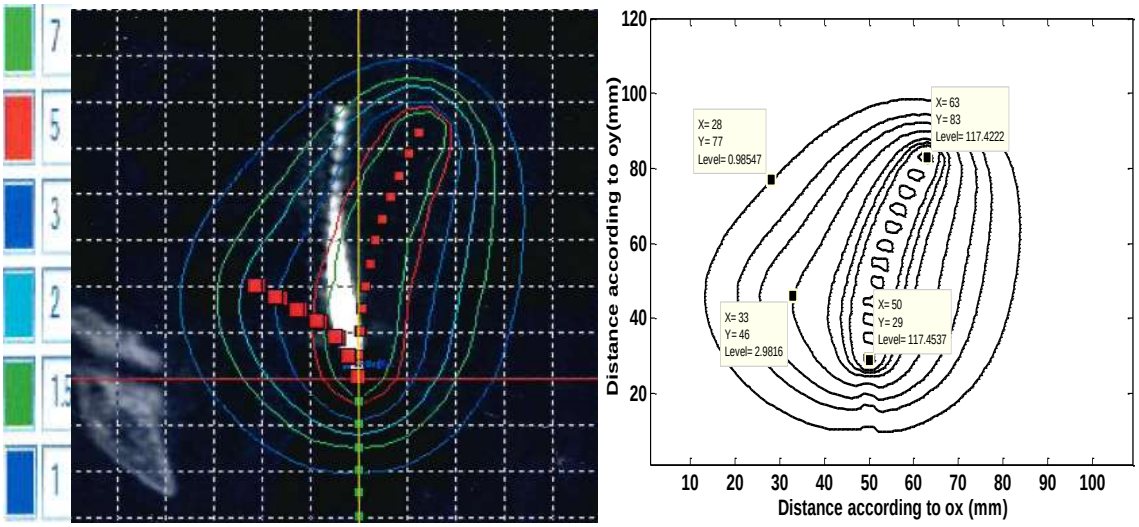
On the source plane of the Uterine Applicator:

- 90 % of the points on the calculated matrix have a relative deviation of 1%-5% which in general are situated over 2mm far enough from the Applicator.
- 8% of these points have a relative deviation between 6% and 10%, from which these points are a bit near the Applicator (1 to 2mm).
- 2% of these points have a relative deviation from 10% to 14%. These points are situated near and around regions where the forms of curved sources are bent or angled (like Vaginal Applicators).

On the source plane of the vaginal applicator: roughly with the same remarks as the previous. In Appendix A7, the comparison of the dose distribution between these two methods is presented for variable treatment time.

Also, the program was tested with a simulation of a linear configuration source of length 1cm on the same geometry previously used for the seed source. The relative deviation in the dose distribution with simulated and calculated results was presented in Appendix A3. The linear configuration source was subdivided in 10 segments (1mm length), As the number of segments increases, the relative deviation decreases and we approach the analogue simulation of a line source.

To check wither the dose is adequate and uniform throughout the target volume, and the extent value in adjacent normal tissue, the DVH was introduced to Prescribe the dose in volume of interest: PTV, OAR or part of them. However, because they do not display positional information, other methods are considered as helping tool [34,12]. As discussed in the next section for the effect of voxel size, we have plotted the Dose Volume Histogram differential DVHD versus dose level for two voxel sizes



(a) (b) (c)

Figure 8. isodose curves for the three curved source: one uterine (central) and two vaginal (extreme) each one is separated with 1.5cm from the other, the calculation is on the central plane.–a- dose in Gy, the number refers to the dose, -b- Sagiplancalculation, the square is $1cm^2$ and the red points are the seed steps. c- this work calculation,

$V_1 = 0.25m^3$ *and* $V_2 = 1m^3$ (consult Appendix A4). The relative deviation between the two curved was 12% and 5% for the maximum and mean value, respectively. A program has been included to calculate the volume of interest between two levels of the isodose surface, where the isodose surface versus dose level for a curved configuration was presented (consult Appendix A5).

Discussion

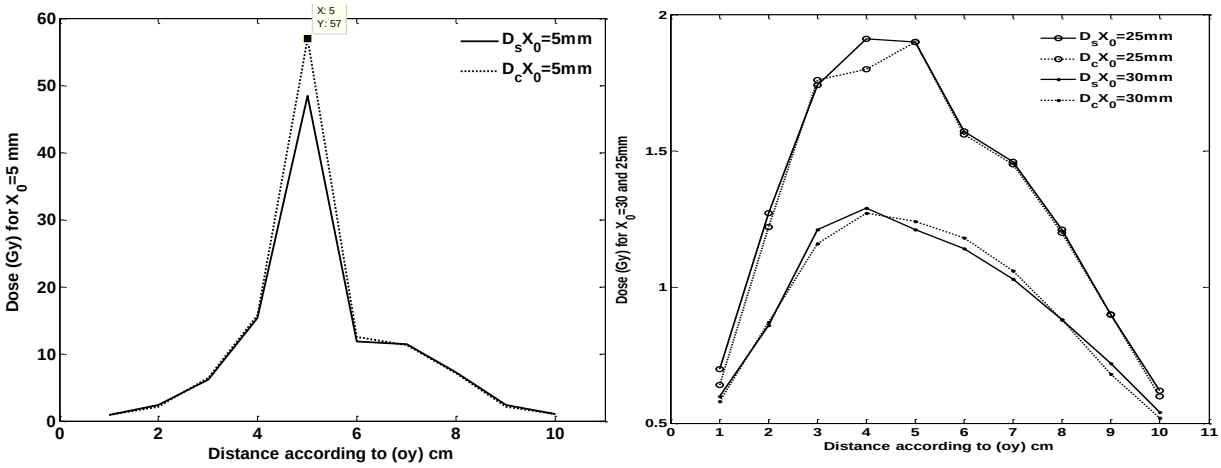
The high percentage of the deviation between the two methods for the few points of the calculation near the Applicators (1-2mm) is caused by three reasons:

-a On the Sagiplan algorithm, the dose calculated at a point p(x,y,z) is based on a Cartesian geometry treatment, which is appropriate because of the non-homogeneous curvature of the Applicator. In this work, the geometry is in the system's polar coordinate; however, it is somewhat limited to homogeneous curvature sources; Near the contact points between the two different homogenous curvatures (as explained in section material and method), we find this deviation. In Appendix A6 we have traced a curved configuration with this later region.

b-The database of the Sagiplan algorithm is supplied by the formalism TG43 (simulation or measurement). In this work, this database is the simulation of the seed source with its Titanium applicator, and the comparison between the two methods will be on the same medium of dose deposited (water). The choice of water medium (without heterogeneity effect) is related to the energy of gamma radiation of the ^{60}Co seed source. In Table Appendix A8 we have cited the cross sections for the process of interaction in the four media of interest in clinical dosimetry, and the ratio of the incoherent scattering cross section is less than 10% between the four media. nevertheless, these two data sources are, in general, in good agreement. As seen in Figure 11, the comparison of the radial dose function $g(r)$ calculated according to results of dose distributed of ^{60}Co seed source simulated and that's calculated by the Sagiplan algorithm according to the formalism TG43.The radial dose function is based on the model line source approximation for the calculation of the geometry function $G(r,\pi/2)$.

$$g(r) = \frac{\dot{D}(r,\theta_0)}{\dot{D}(r_0,\theta_0)} . \frac{G(r_0,\theta_0)}{G(r,\theta_0)} \quad with \quad \theta_0 = \frac{\pi}{2}, \tag{4}$$

We find a good agreement between the two methods. Some commercialized programs used the model of punctual source approximation, while the Sagiplan algorithm is based on the line source model. In contrast to the anisotropy function, where the dose calculated or measured through different methods will not be the same in regions where the statistical uncertainty in simulation matrix is important around the seed source axis (fewer events on the dose deposited). At some points in these regions, we can find this difference in relative deviation (As announced previously in Appendix A6 for curved configuration).



(a) (b)

Figure 9. Variation of dose on the uterine plane according to (oy) for different coordinates (ox) with fixed treatment time. D_S from Sagiplan, D_c this work. -a- on the left of the central axis . –b- on the left and near the central axis , c- on the right and near the central axis -d- on the right of the central axis.

This is the interesting reason for the difference in the relative deviation between the two methods. The choice of the voxel size is an important factor in ensuring accurate dose calculation, especially in regions near the radioactive source or the interface between media. A good resolution in the calculation matrix certainly depends on the voxel size. In this concept, some Modern TPSs that wish to implement the Monte Carlo Algorithm have been employed in modern Radiotherapy due to advances in Computing power. The choice of the voxel size and statistical uncertainty is a compromise between time-consuming and precise calculation [35]. The concept of the scoring dose in voxels is based on the dose averaged at the centre of the voxel [36] . Thus, estimating the dose on a large voxel in the simulation matrix will not be advisable with a divergence effect in regions of the dose gradient and in regions were photons are hardly attenuated. We have traced in figure A6 the divergence effect of the primary dose of photons emitted from the ^{60}Co seed source, this effect is purely geometric factor, and the mean value of the dose calculated on the centre of voxel with step size 0.1mm is closer to the real value in contract with step size of voxel 0.5 mm. At the start of this work, the thickness of the annular voxel in the simulation matrix was different (0.7 mm, 2 mm and 12 mm as seen previously) and the step size on the two axis in the calculation matrix was 1 or 2mm, sow the results compared with Sagiplan algorithm was: 75%, 15% and 10% of points have 1-10%, 11-20% and 20-35%r respectively. After reducing the thickness of the annular voxel Δr and Δz to 0.5 mm and 0.2 mm in the simulation matrix and the voxel size 0.25 mm^3 in the calculation matrix, the relative deviation was reduced as cited previously. The voxels size on Sagiplan algorithm is 0.001 mm^3 and with another reduction in the voxels size in the simulation and calculation matrix, the results will still converge. We are limited to the power of computing machines and processors; it is a compromise and depend on the situation being treated.

To complete the present work in this article, we have drown in figures-10 a b c and d- some configurations of different modalities used in clinical routine such as: Intracavitary cervical cancer, wich is the most gynecological cancer in development, interstitial like Breast which is the most common cause of cancer related death in females, Intraluminal treatment for endobronchical palliative treatment of abstractive symptoms and Esophageal and gastric cancer. The majority of this modality requires catheter applicators of different diameters and rigid Titanium Applicators, like Intracavitary treatment [1,2].

Conclusion

Dose calculation in Brachytherapy oncology is a crucial objective for estimating the prescribed dose in the regions of interest. This prescription depends on the materials and methods used to guarantee it. Some methods are applied in simple situations but become less precise in complex situations with source configuration, spectral energy complexity and medium heterogeneity.

The method that remains adequate in real-life situation is the Monte Carlo technique. Because of the numerous databases on the physics of radiation interaction with matter and the calculation algorithms embedded in it, the only obstacle is the calculation time [45,37,38]. Here, other methods are used to achieve the approach to prescribing dose calculation, like the superposition and convolution methods.

The method used in this work is the superposition technique, a mathematical tool based on data generated by the user code DOSRZnrs. This latter simulates the dose contribution deposited at each electron step in the water medium; the electrons are generated by photons from an HDR ^{60}Co seed source injected on its Titanium applicator or catheter. In this first phase, we define a simulation matrix. In the second phase, the seed source is injected into a Titanium applicator or catheter to give different configurations of curved/linear sources, and the superposition program does the calculation of the dose distribution in a calculation matrix for a curved/linear

configuration by summing all doses from each step of the seed source in its path on the applicator, this seed source doses is the database of the simulations matrix. In this second phase no MC simulation is made.

This work was compared with the Sagiplan algorithm, based on the TG43dosimetry protocol, and good agreement in results for the dose calculated withthe two methods was obtained.With perspective, it's desired to include Cartesian geometry in the mathematical treatments to cover more complex curvature configurations and include the heterogeneity effect in the case of different media.

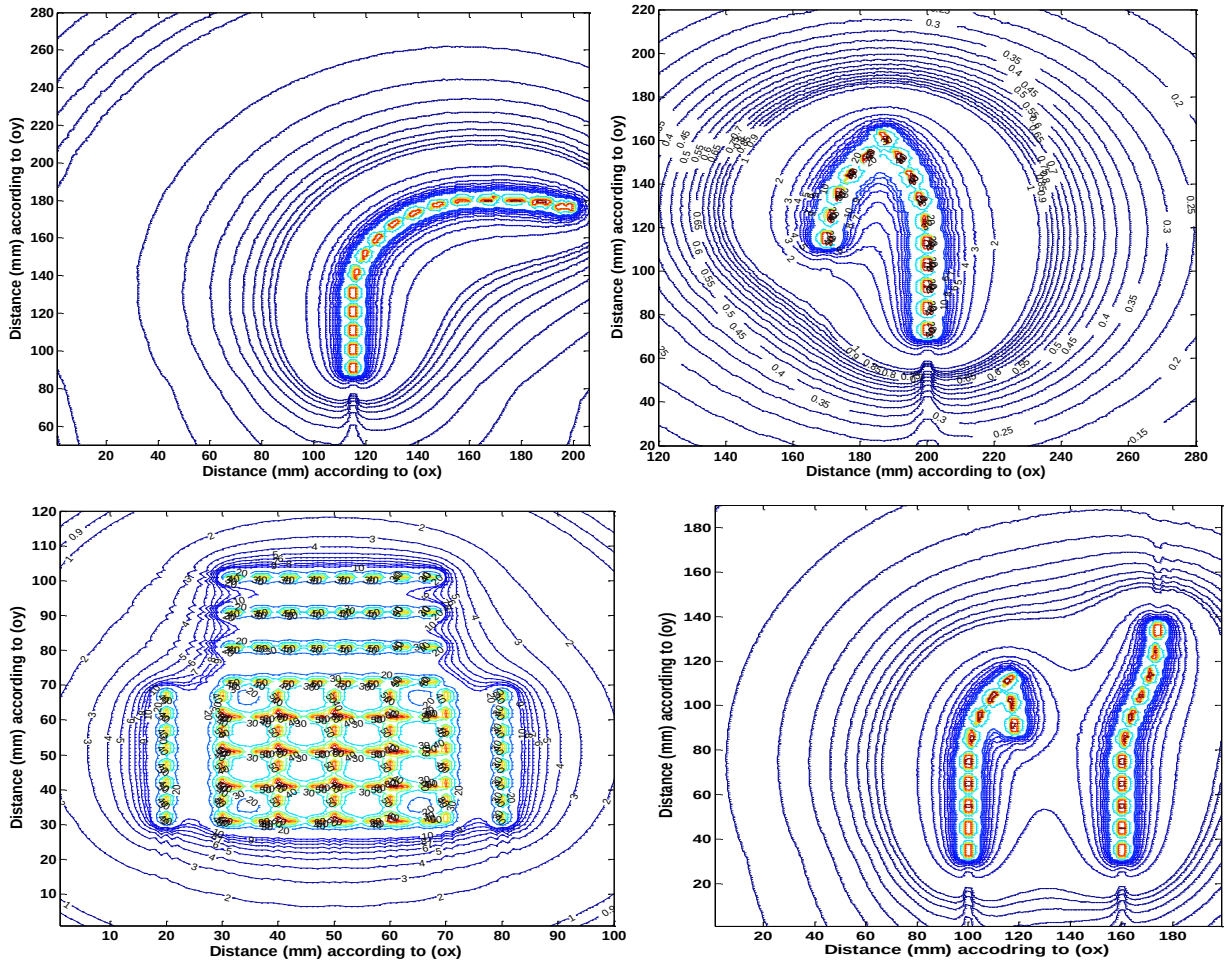


Figure 10. Some examples of configuration used in clinical routine, the stapes calculations according to (ox) and (oy) are 0.5mm. –a- curved/linear configuration for oesophageal treatment –b- vaginal Applicator. -c- two group of linear sources oriented with 90° superimposed -d- bronchus and oesophagus treatment.

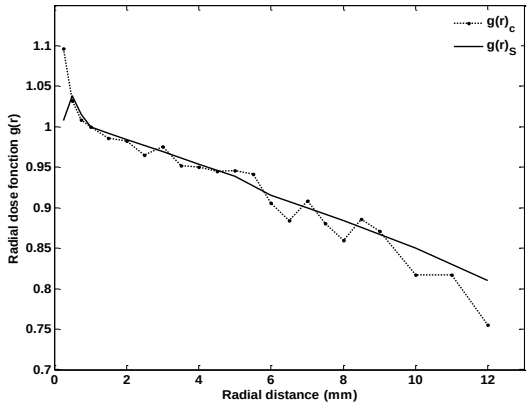


Figure 11. Comparison of the radial dose function $g(r)$ calculated with Sagiplan and this work. We used the line source model to calculate the geometry function $G(r,\pi/2)$.

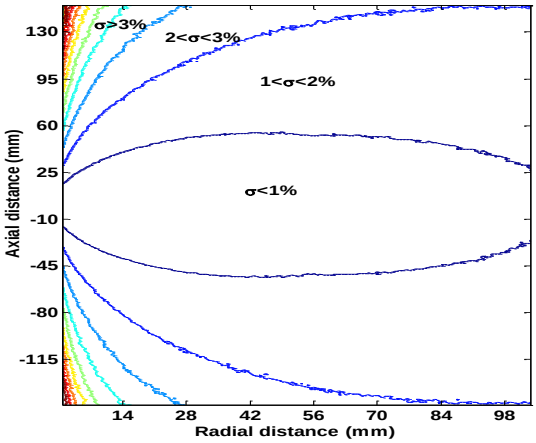


Figure 12. Curves limits of uncertainty σ for isodose distribution of the ^{60}Co seed source.

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Appendix

Tableau A1.resum of different options used on the file 'rgsinput' in users code. On the user code 'DOSRZnrc' the options in variance reduction technique are not used

		Typ of input	description	Option choosed
Input and results Control		IRESTART	option used to begin a new simulation	First or restart
		OUTPUT OPTION	Physical quantity to be introduced on the 'egslist file'	Material and dose summary
		STORE DATA ARRAYS	Storing results for next simulation	yes
		ELECTRON TRANSPORT	electrons transport techniques	normal
Monte Carlo Input		NUMBER OF HISTORY	number of history or event to be simulated	default 20000
		MAXIMUM CPU HOURS ALLOWED	maximum simulation time.	default 90 hour
		IFULL	quantity to be calculat	Dose and stoppers
		STATISTICAL ACCURACY SOUGHT	Simulation intel reaching statistical accurcy	default 0.00%
		SCOR KEMA	quantity to be Scoring	Kerma and dose
Geometry		METHOD OF INPUT	Two methods of inputs : groups of voxels have the same geometry or individual	by group
		SLAB THICKNESS and RADII	Thickness of Slab and radius cylinder	300 concentric cylinder ($1^{st}-5^{th}$ arbitrary cylinder thickness for source). 295 cylinder and 801 plans for water medium with same thickness 0.5mm
Materials		MEDIA	Transport media	H_2O , Co , $Stell$ Air, $Plastic$, Ti
		DESCRIPTION BY : REGIONS or PLANES	Two methods of inputs : regions or Plans. A number of plans have the same medium or each medium is individual	PLANES
source Inputs		INCIDENT PARTICULE	type of incident partial	PHOTON
		SOURCES NUMBER	source configuration number	Cylindrical geometry source 3
		SOURCE OPTION	source dimensions	$\Delta r = 0.3m$ $\Delta Z = 3.5mm$
		INCIDENT ENERGY	Type of incident spectre energy	On photon
		INCIDENT KENITIC ENERGY	Kenitic energy incident	1.25 MeV
Monte Carlo Transport Parameters	PHOTONS	GLOBAL PCUT	Cut off energy of photons	10keV
		Bound Compton scattering 'IBCMP'	Binding effects of atomics electron with nucleus	on
		Brems angular Sampling 'IBRDST'	Sampling angular distribution of Bremsstrahlung photons	KM (Kocn-Mots formula)
		Brems cross sections 'IBR_NIST'	Cross section of Bremsstrahlung photons	NIST National Institut standards technology)
		Pair angular Sampling 'IPRDST'	Sampling of angular emission in event of pair. production	Simple Leading term of angulair distribution –KM-
		Photoelectron angular sampling 'IPHTER'	Sampling of angular emission in event photon absorption	On Sauter's formula for Kshell photon absorption
	ELECTRONS	Rayleigh scattering 'IRAYLR'	Cohérent scattering (Raleigh scattering)	On Raleigh Cross section
		Atomic relaxations 'IEDGFL'	After each photon absorption event atomics relaxation will occur.	On Simulation of photons fluorescence and electrons Auger
		GLOBAL ECUT	Cut off energy of electrons	521 keV
		Boundary crossing algorithm 'BCA'	Transport algorithms of electrons crossing the boundary between regions	EXACT exact formula of Parameter Rediused Electron Stap Transport Algorithm
		Electron-step algorithm	Algorithms transport of electrons in media	PRSETA.II

	Spin effects	relativist spin effects of electrons on elastic scattering	on
	Maximum fractional continuous energy loss per step' ESTEPE'	maximum fraction of energy loss on CSDA. Approach (Continuous Slowing Dawn Approximation)	0.25
	Skindepth for BCA	Distance to interface were algorithm BCA will go into simple scattering (Boundary Crossing Algorithm).	0.3 MFP (Mean Free Path)
	Maximum first elastic scattering moment per step 'XImax'	maximum fraction of energy loss in discreet event (simple scattering).	0.5
variance Redection Technique	BREM SPLITTING	Splitting of photons with there wait is reduced on an interaction.	off
	ELECTRON RANG REGECTION	electron history is terminated if his residual energy is less to cross the next region	off
	PHOTON FORCING	photons are forcing to interact on specified regions	off

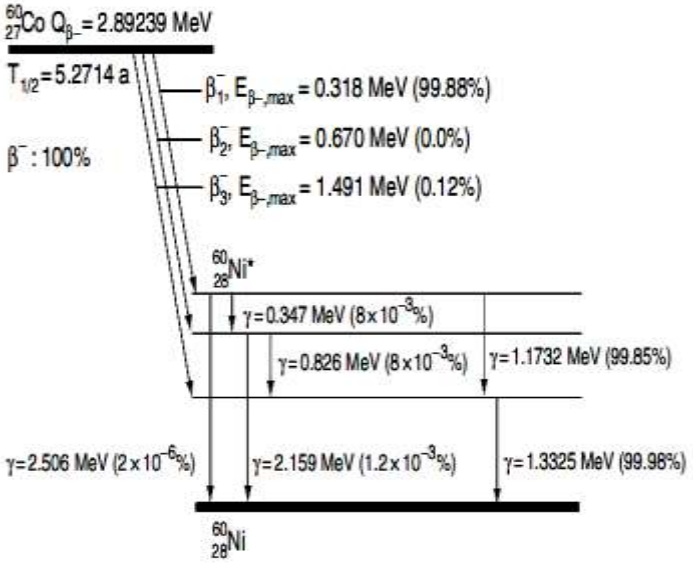
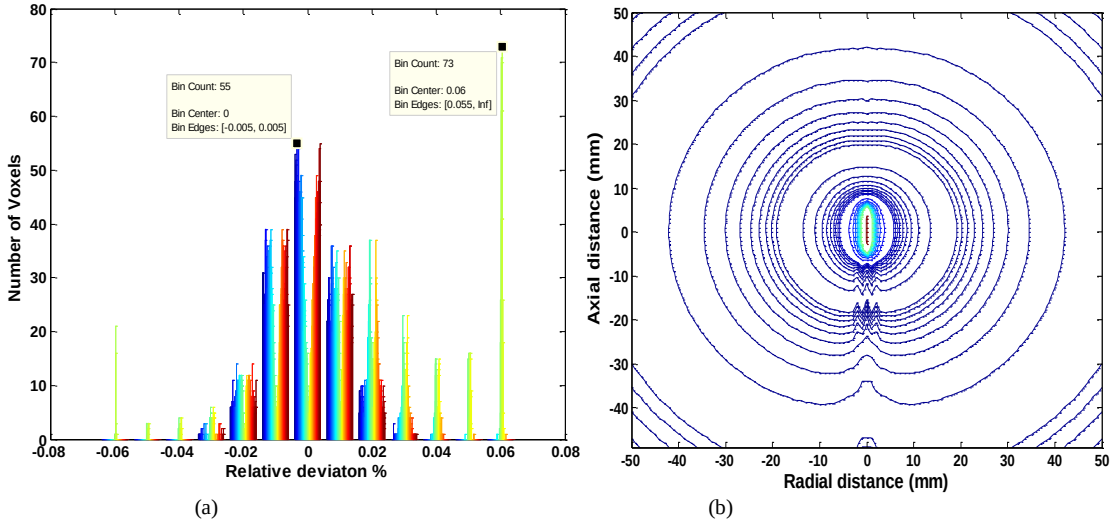
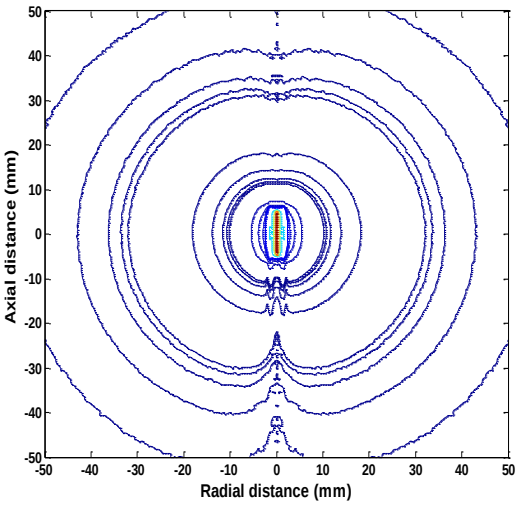


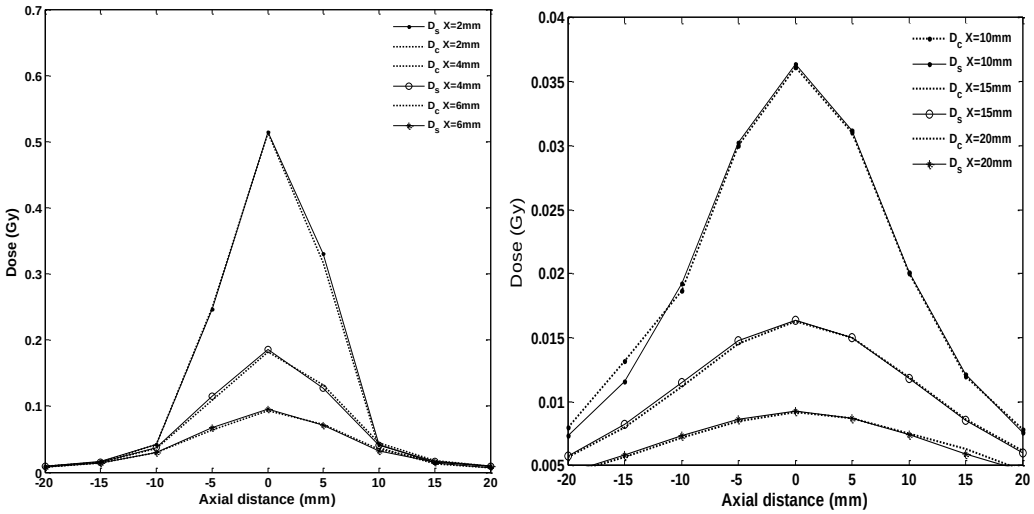
Figure A2. Mode of disintegration $^{60}_{27}Co$ isotope [22]



(a) (b)

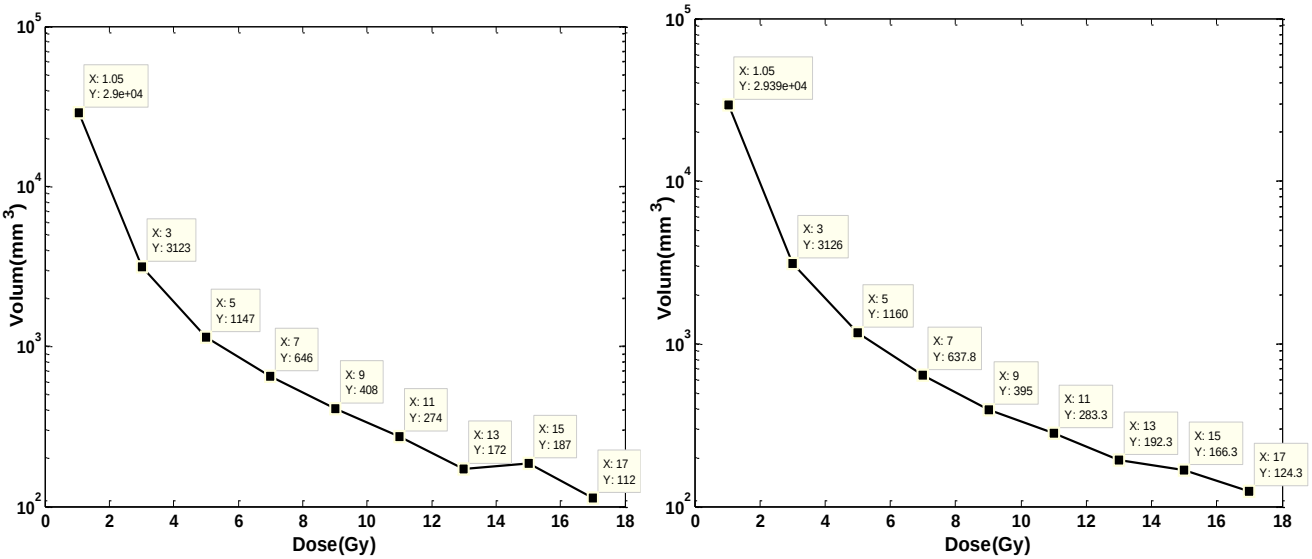


(c)

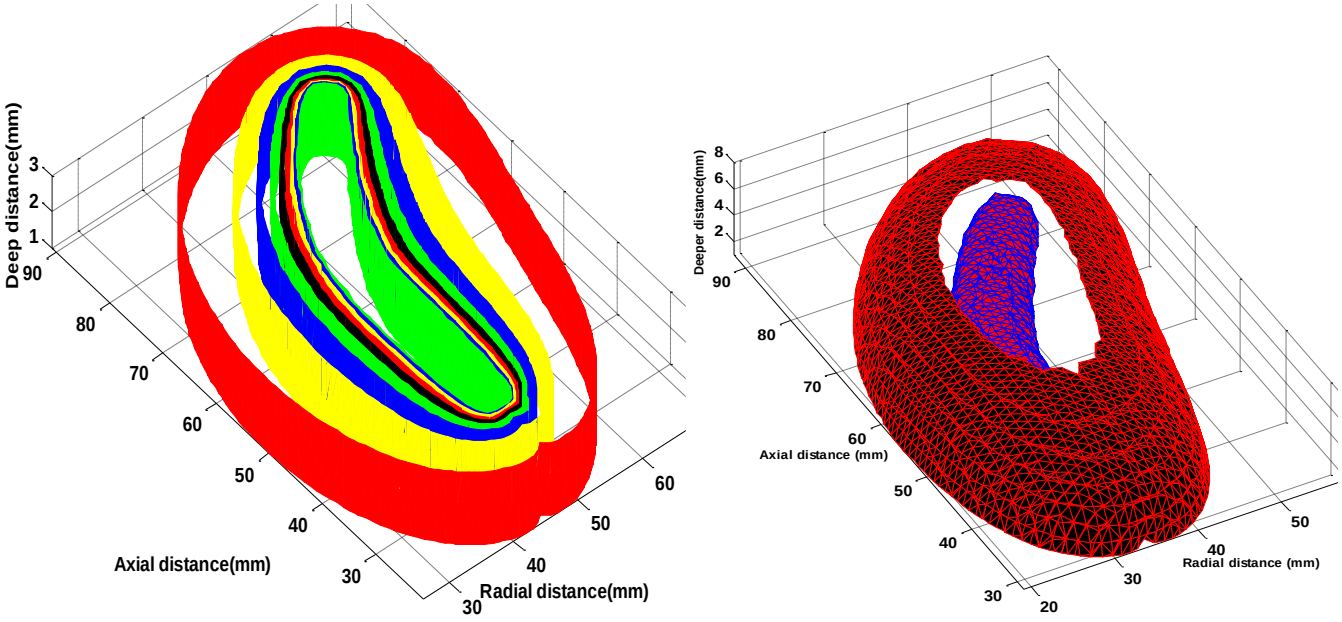


(d) (e)

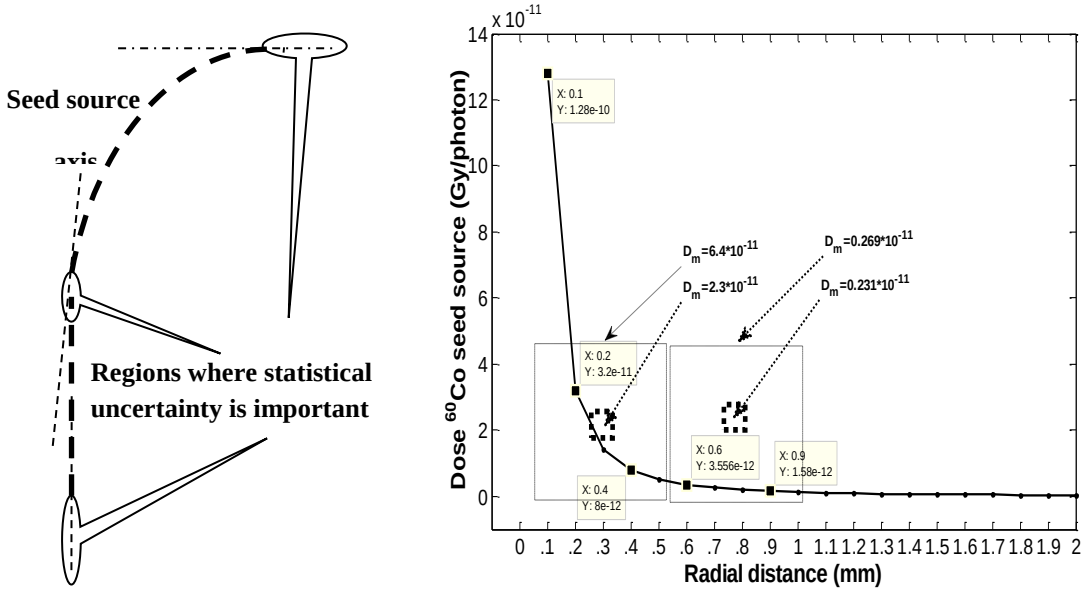
Figure A3. -a- relative deviation for dose distribution calculated and simulated for linear configuration source L=1cm .–b- isodose curve for source L=1cm subdivased to 10 segments and calculate with this program. -c- isodose curve for source L=1cm simulated with user code DOSRZnrc. –d- and –e- comparisen between dose calculate and simulated for source L=1cm, the source was subdivided to 10 segments for on the calculation program.



A4 Dose Volume Histogram DVHD for curved configuration versus dose, the seed source injected in Titanium Vaginal Applicator. voxel volume Left figure $V = 1m^3$, right figure $V = 0.25m^3$. The maximum and the mean relative deviation of Volume for the two calculation is 12% an 5%



A5 isosurface dose for different dose level for curved configuration as privies. Left: 3 plans superimposed dx=dy=dz=1mm , right: 8 plans superimposed dx=dy=1mm and dz=5mm (here the thickness of isosurface was exaggerated to display the volume between dose level for DVH calculation).



A6.a. curved linear form configuration where three regions of important statistical uncertainty are sited with the reason of the hardly attenuation of photons wish result for a fewer events the dose deposited.

A6.b. divergence effect of the primary dose of photons emitted from the ^{60}Co seed source calculated for different voxels sizein radial distances on a annular geometry. this effect is purely geometric.

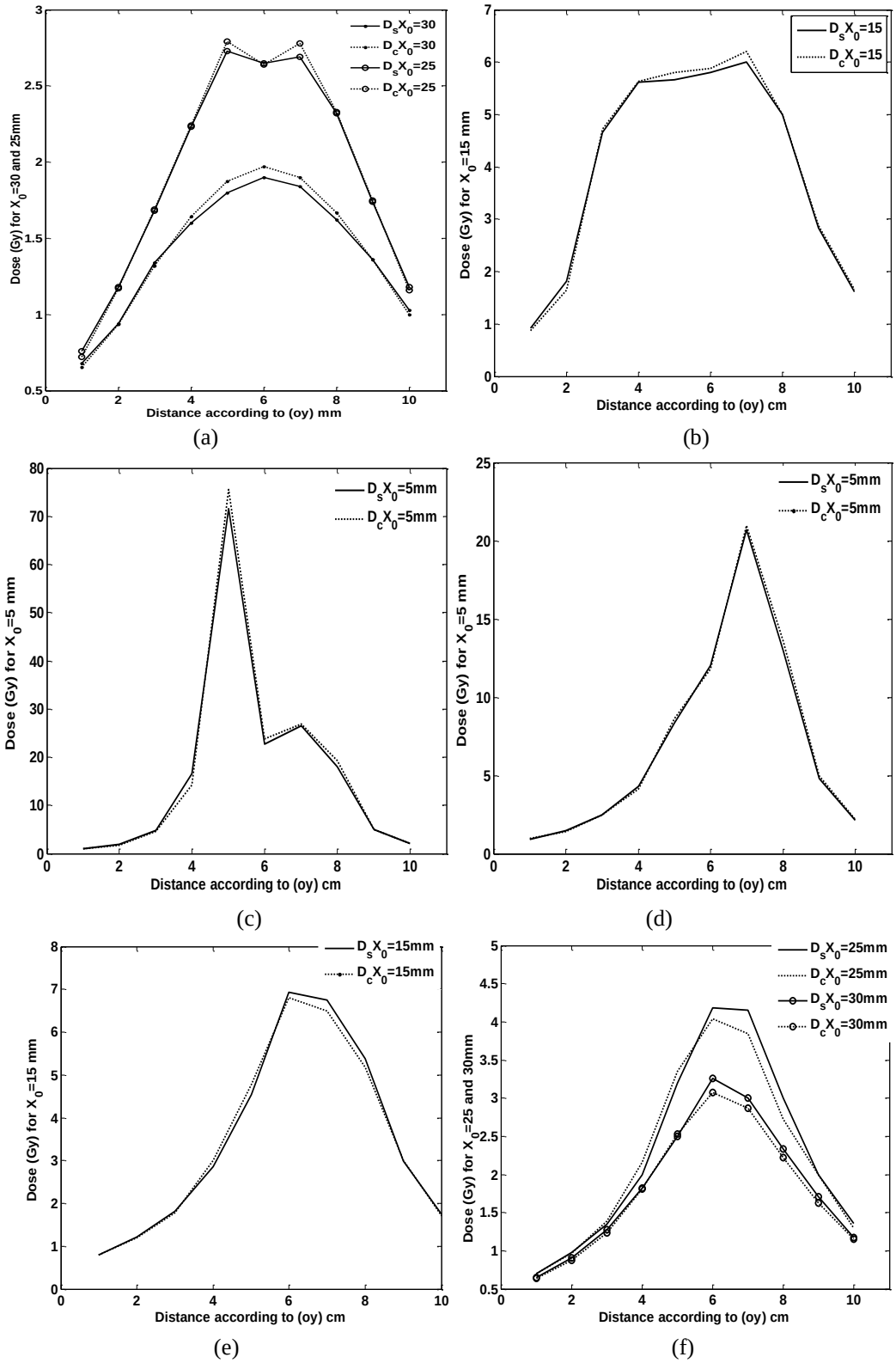
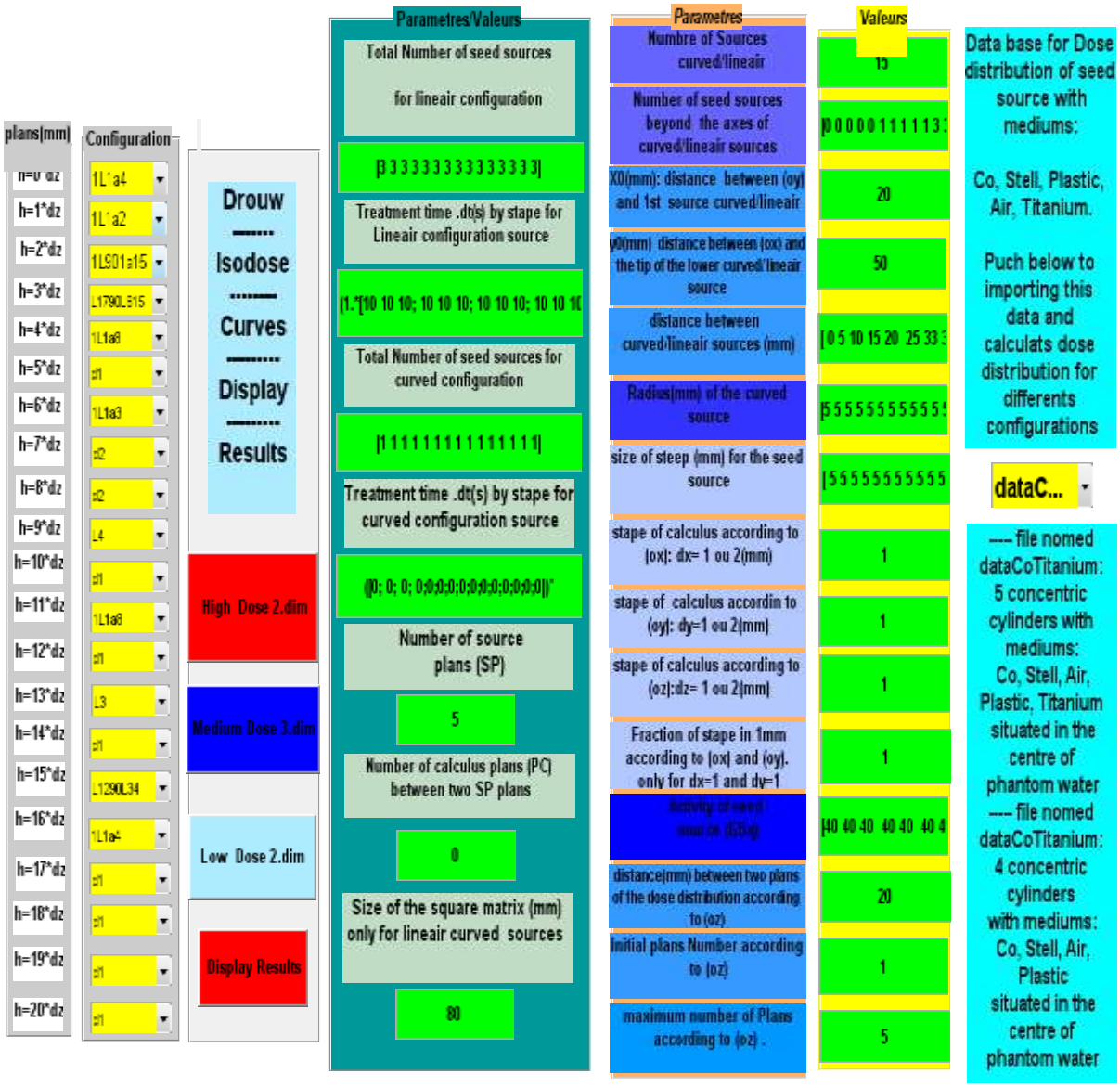


Figure A7. the variation of dose distribution on uterine plane for variable treatment time according to (oy) direction for different coordinates (ox). D_S is dose calculated by Sagiplan and D_c is that calculated by this work. -a- and -b- on the rite of the central axes for (X_0=15 , 25 and 30mm) . -c- on the rite and near the central axes for(X_0=5mm). -d- on the left and near of the central axes for (X_0=5mm). , -e- and –f- on the left of the cetral axes for (X_0=15 , 25 and 30mm).

Table A8. The cross-section values for the four physical processes of the photon with medium for four interesting media in radiotherapy physics (from National Institute Standards and Technology-NIST-).

	$\bar{Z}$	$\rho(kg/m^3)$	$N_e(elec/m^3)$	$\sigma_{Inc}(cm^2/g)$	$\sigma_{Coh}(cm^2/g)$	$\sigma_{Ph.e}(cm^2/g)$	$\sigma_{PP}(cm^2/g)$
				$E_{ph}=0.6MeV$			
Soft tissus	7.64	1040	$3.44.10^{29}$	$8.88.10^{-2}$	$14.4.10^{-5}$	$11.4.10^{-6}$	0
Water	7.51	1000	$3.34.10^{29}$	$8.94.10^{-2}$	$15.6.10^{-5}$	$11.7.10^{-6}$	0
Air	7.78	$1.2.10^{-3}$	$3.6.10^{26}$	$8.04.10^{-2}$	$15.3.10^{-5}$	$12.5.10^{-6}$	0
Bon	12.31	1850	7.10^{29}	$8.53.10^{-2}$	$26.6.10^{-5}$	83.10^{-6}	0
				$E_{ph}=1.25MeV$			
Soft tissus				$6.27.10^{-2}$	$3.33.10^{-5}$	$2.26.10^{-6}$	$16.8.10^{-6}$
Water				$6.32.10^{-2}$	$5.6.10^{-5}$	$2.33.10^{-6}$	$17.8.10^{-6}$
Air				$5.68.10^{-2}$	$3.53.10^{-5}$	$2.48.10^{-6}$	$17.8.10^{-6}$
Bon				$6.03.10^{-2}$	$6.15.10^{-5}$	17.10^{-6}	$23.2.10^{-6}$



AppendisA9. the graphical user interface of the program. There are panels for geometric and dosimetrics variables input (gray color) and panels for explication and indication (bleu color) and puchbuton and pup menu to display results on figures or tables (yellow color).