How to use “Visual Monte Carlo dose calculation”

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Site VMCsoftware.com

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Contents

1. Introduction

This help file describes Visual Monte Carlo (VMC) dose calculation and explains the steps necessary to run VMC dose calculation. VMC dose calculation was written with the objective of calculating tissue and effective doses. ICRP voxel phantoms of the male and female human body are provided. The radionuclide library includes commonly found sources in the workplace. The programming work and the validation of VMC dose calculation started in 1998 and have continued to the present day.

The main objective of all this work is to calculate the tissue doses and the effective dose for the geometry and radionuclide in question. Results from intercomparisons and validations show that doses calculated with VMC can be considered to be within the range of ± 5% of the “real doses”. Size and shape differences between the real exposed person and the mathematical phantoms are the main source of uncertainty. For future work, a range of male and female mathematical phantoms differing in height and weight will be included in VMC dose calculation. Phantoms of 1 year, 5 years, 10 years and 15 years children will also be included. VMC dc can be run at the same time any other Windows program is being run, such as WORD. Two or three VMC dc projects may be run at the same time.

2. Windows compatibility

VMC dose calculation is written in VB6 (32 bits), and I am working on the up-grade to Visual studio VB14 (64 bits). Although Windows states that all programs are “backward compatible”, this is not always correct and it is advisable to follow the next steps to avoid any running problems. After the setup has been run, click with the right mouse button on the VMC executable, click on the page for compatibility and fill in the following:

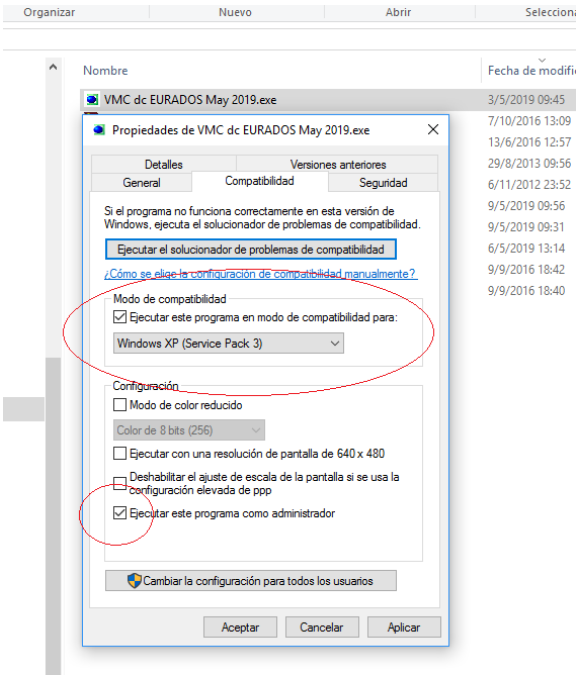

Figure 1. Compatibility setting for VMC in Windows 7 or 10.

3. Point source projects

3.1 How to start a point source project

With the radionuclide button chosen on the first page, choose whether to create a new project or to open an existing project file.

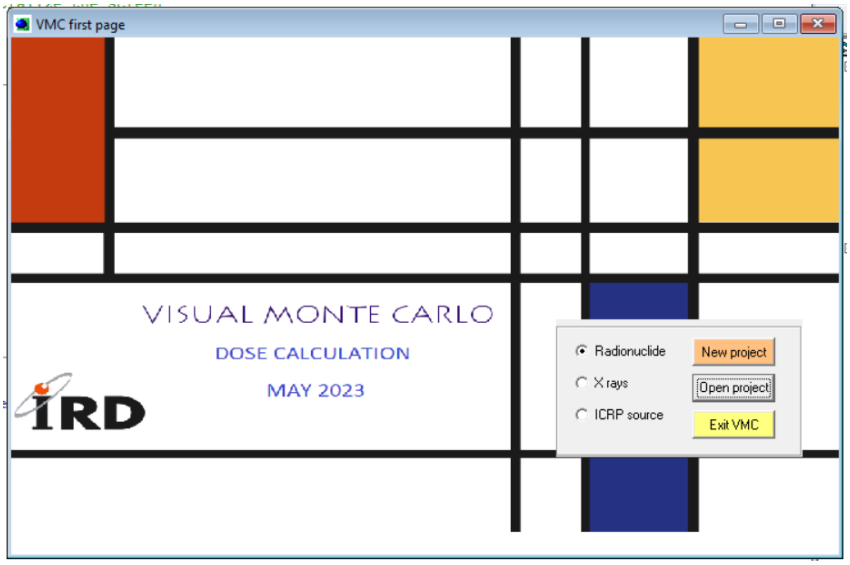

Figure 2. First page of VMC dose calculation.

There are three options, to create a new project, to open an existing project or to exit the program. The configurations of an existing program are saved in a file in the folder C:\VMC dc\Projects\... and can be opened at any time (open project) to repeat a run. If the button "Radionuclide" and "new project" are chosen the following screen opens, see Figure 3.

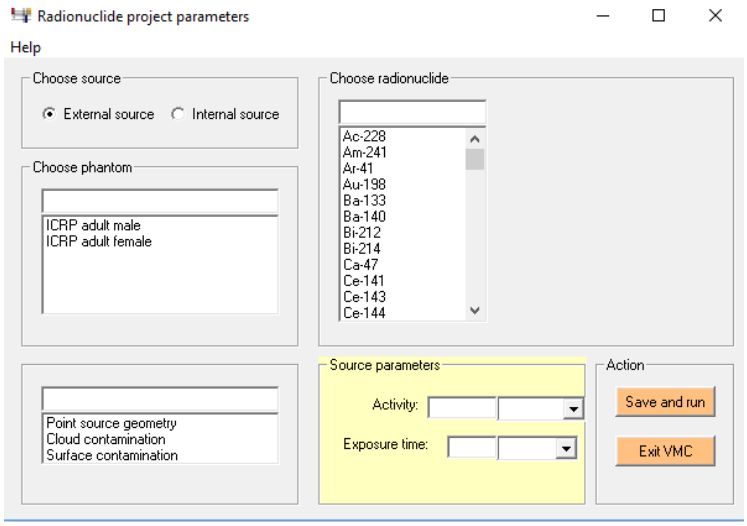

Figure 3. Define the new radionuclide project.

3.2 Defining the project parameters

First choose the phantom. Available phantoms are the ICRP male and female adult phantoms.

Secondly choose the point source geometry. The geometry for the point source is a room 5 m x 5 m x 3 m height with the phantom placed in the middle of the floor. Photons that hit the phantom which are reflected from the ground and walls also contribute to the dose.

Choose the radionuclide. In all cases, it is considered that the radionuclide is in equilibrium with its daughters. For example, in the nuclear transformation ^{137}Cs → ^{137}Ba (stable) there are three possible decay paths and in one path the ^{137m}Ba emits a 0.662 MeV photon. The yield of this photon per nuclear transformation of ^{137}Cs is 0.846, signifying that in 100 nuclear transformations of ^{137}Cs, on average around 85 transformations will emit a 0.662 MeV photon. VMC dose calculation simulates for each "history" the photon emission due to one Becquerel or one nuclear transformation of the chosen radionuclide, followed by the relevant nuclear transformations of its daughters. It is therefore possible to simulate one history of ^{137}Cs, and no photon be emitted. In this case, by chance, the ^{137}Cs decayed to ^{137}Ba without emitting a 662 keV photon.

The three natural decay chains are included. A "short" ^{238}U → ^{90}Th → ^{91}Pa → ^{234}U chain is also included. It is assumed that the radionuclides in a chain are in secular equilibrium. If a mixture of more than one radionuclide is required please send the details to my email address.

When the radionuclide has been chosen, a table will appear with the photon energies and their respective yields included in VMC dc. Photon energies with yields above 1% and energy above 15 keV are included.

Enter the source activity. For the point source the activity is in Bq or Ci. Enter the exposure time of the phantom in seconds, minutes or hours.

3.3 Saving the project

Once the above project information has been established, click on the button "Save and Run". The screen shown in Figure 4 will open. Choose an appropriate project name. The project data, this project file. When you click on "Save" the project will be saved as a text file to C:\VMC dc\Projects.

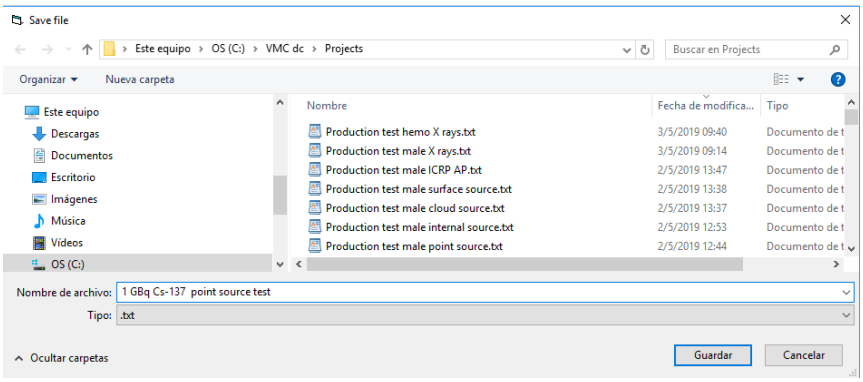

Figure 4. The save project screen.

3.4 Setting up the point source geometry

After the project has been saved, the screen shown in Figure 5 will open.

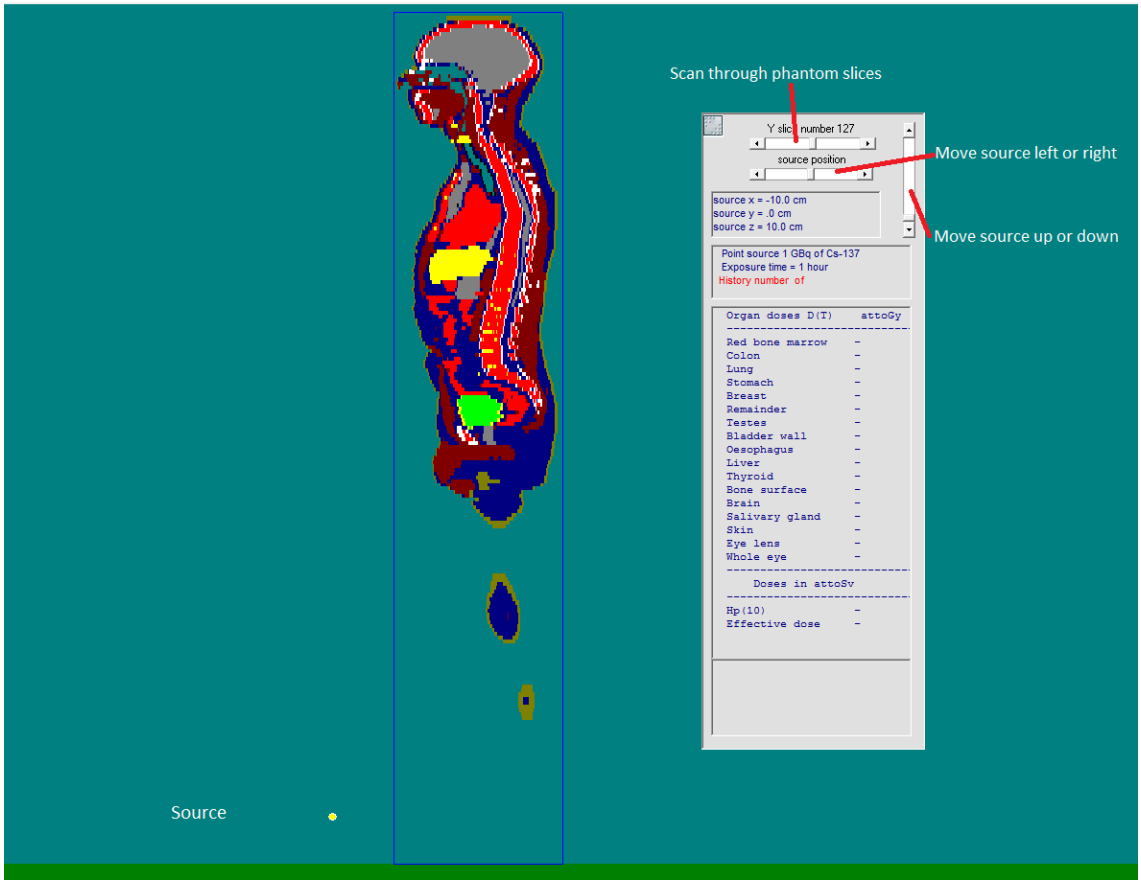

Figure 5. The initial project screen. A right click on the mouse will enable you to zoom in and out of the geometry.

If the control frame is in the way of the phantom, click on it and hold the mouse button while you drag and drop it to an appropriate position. The ICRP male phantom is shown in saggital (side) view. It is possible to scan through the phantom by clicking on the Y slice bar. The Y slice number is shown. The source may be moved left - right by clicking on the source position bar or up and down by clicking on the vertical bar. The X, Y, and Z positions of the source are shown in the text window.

The source may now be positioned relative to the phantom see Figure 6.

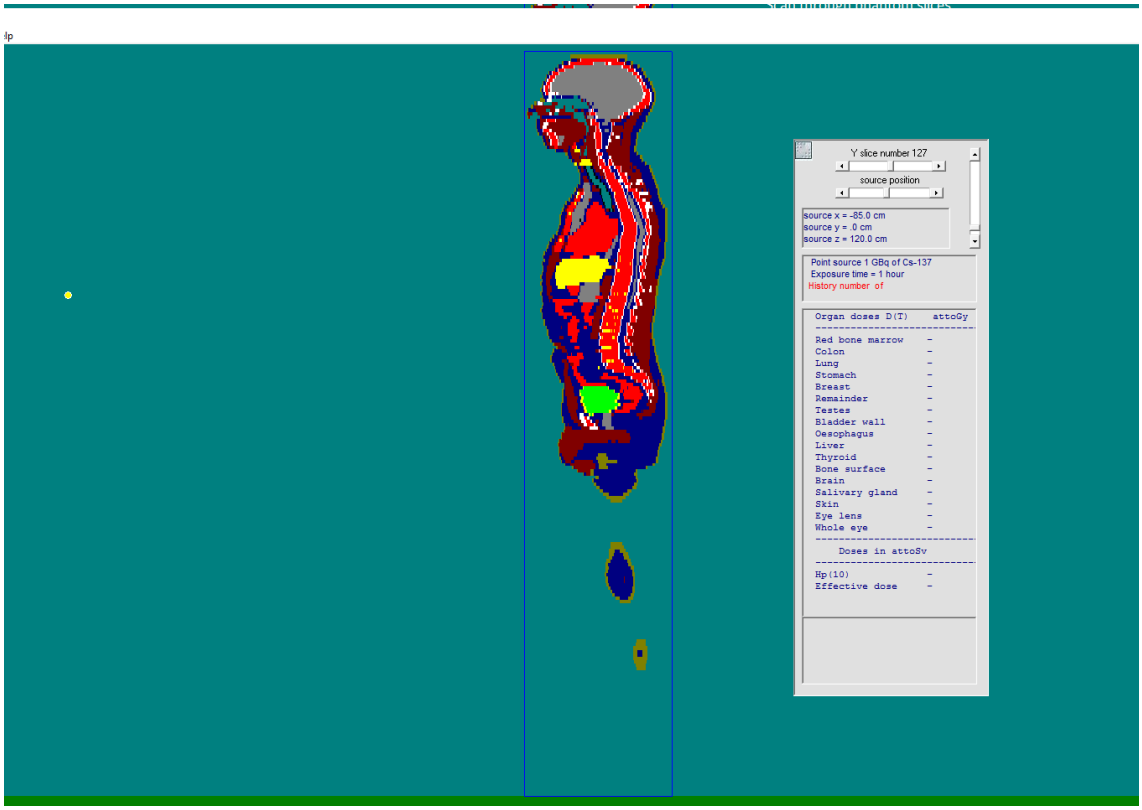

Figure 6. Positioning the source in side view

The source has now to be positioned in the Y axis. On the menu bar, click on “Views and graphics” → “Front View” and the following image will be seen.

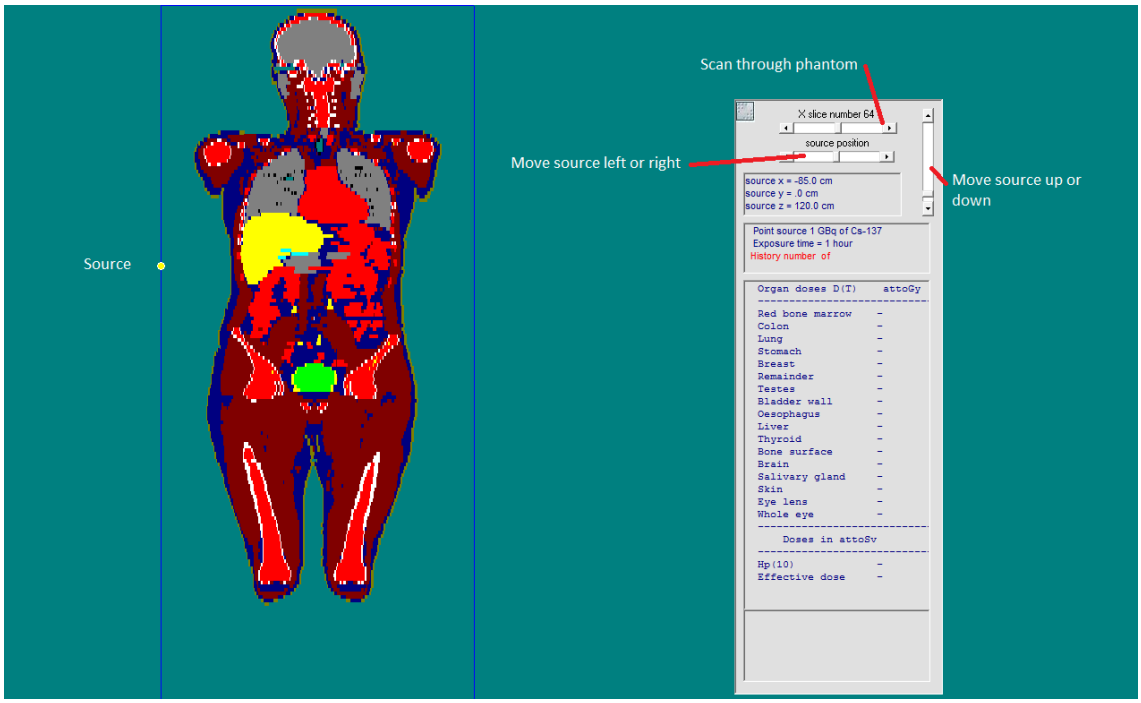

Figure 7. Positioning the source in front view

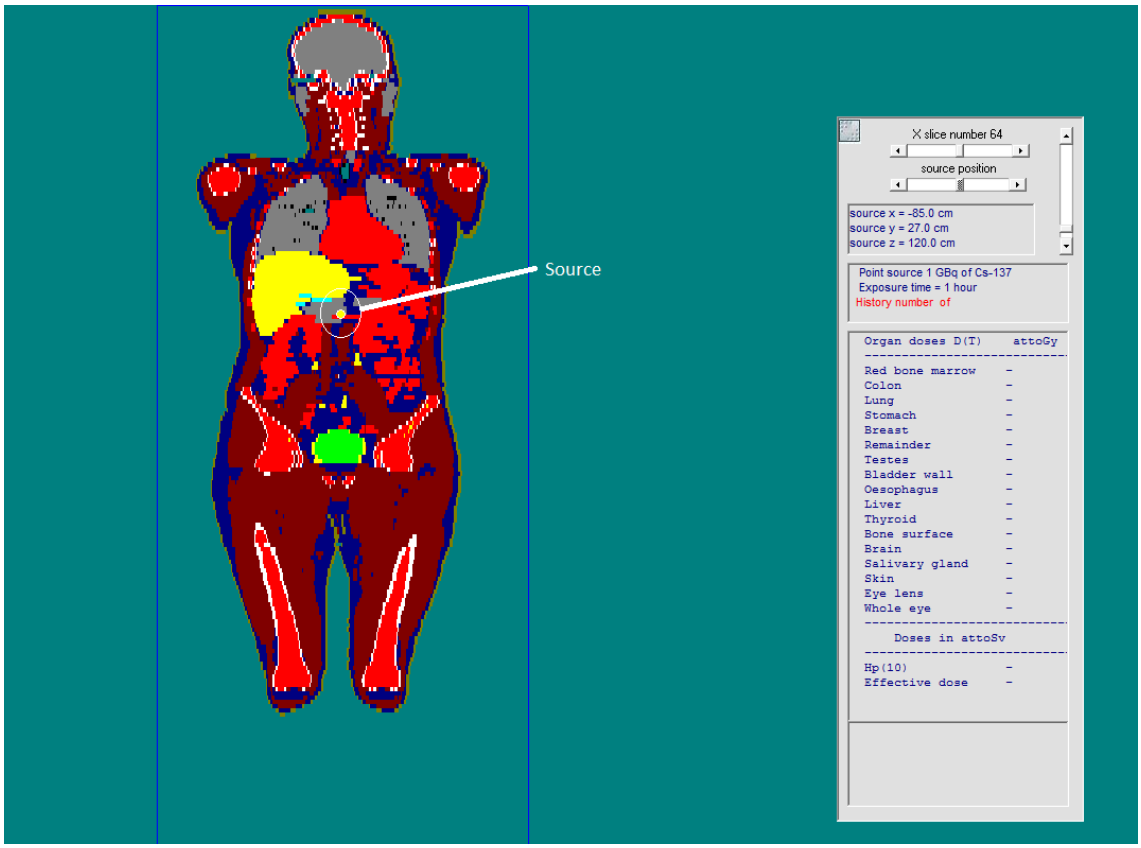

Figure 8. Move the source to the middle of the phantom

I suggest that for the run you go back to the side view by clicking “Views and graphics” → “Side View”. Alternating between the side, front and top views will enable the source to be positioned within a millimeter or two of the desired position.

3.5 Making the run

The project has been defined and the point source is in position, it's time to calculate the doses. To start the run, choose the number of histories required from the menu “Run options” → “Run 10,000 histories”. 10,000 histories may be used for a quick check or demonstration, 10^7 histories may be used for a rough estimate of the dose. 10^8 histories may be used for a full calculation run. Each history represents one Becquerel; one nuclear transformation of the radionuclide is simulated.

The more histories run, the longer the time required and the more precise is the calculation of the doses, especially to smaller organs such as the thyroid. For more detailed studies of the eye lens, whole eye or breast dose, around 10^9 histories may be needed. 10^7 histories require around 4 minutes on a modern computer.

When the program is running, the graphics shows where the photon started, it´s initial direction, and any photoelectric (yellow circles) or Compton (blue circles) interactions in the phantom. The graphics slows down the run considerably, therefore for longer runs (Runs > 100,000) it is recommended to turn the graphics off. The number of histories run is shown on the information frame. The run ends when the number of histories requested is equal to the number of histories run. For an example of the graphics produced during the run, see Figure 9 below.

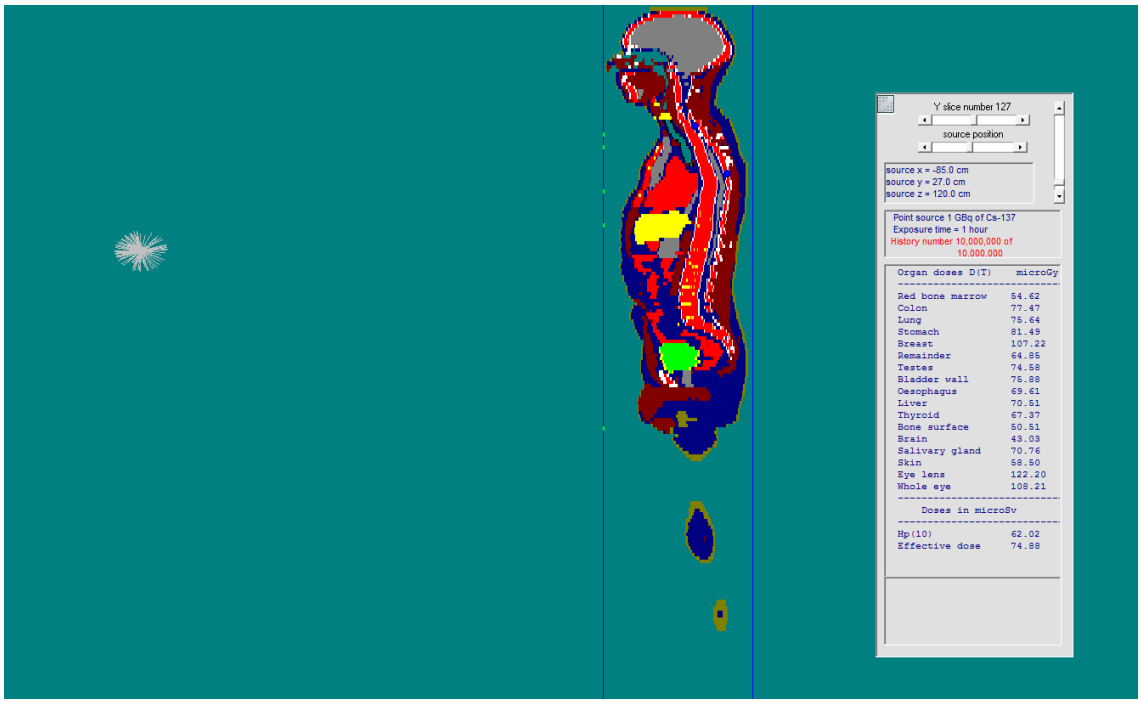

Figure 9. Side view of the ICRP male phantom, showing 10^7 histories run with the I GBq Cs-137 point source. The green rectangles are the points where the photon hit the outside border of the phantom matrix.

3.6 Projects with point sources inside the phantom matrix

Accidents with high activity sources such as those used for industrial radiography have serious health consequences and are thankfully infrequent. VMC dc allows this type of accident to be simulated and permits the estimation of the dose to tissues near to the source so that isodose lines can be draw that in turn can help medical treatment.

A 1 TBq source of Ir-192 is used as an example. The source was placed in the back pocket of a worker´s trousers for 60 minutes, see figure 10.

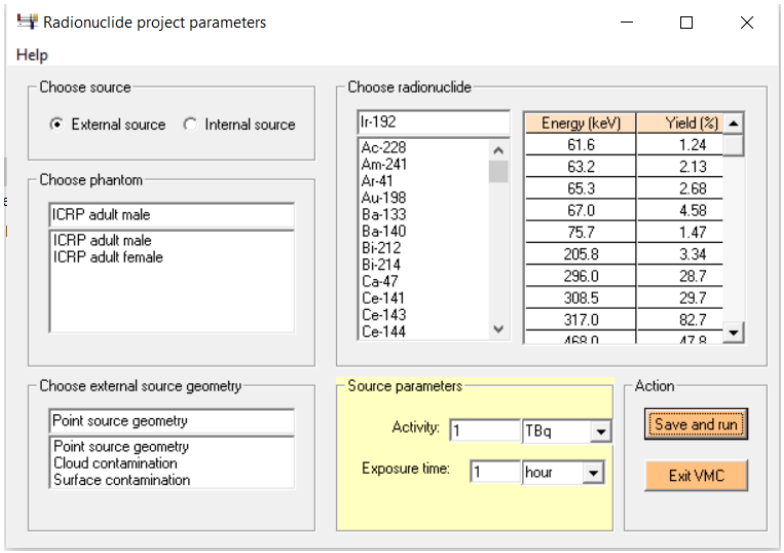

Figure 10. Define the radionuclide project.

Save the project. Move the point source to the following position, see Figures 11 and 12. The VMC dc source is positioned to reproduce the source position inside the back trouser pocket.

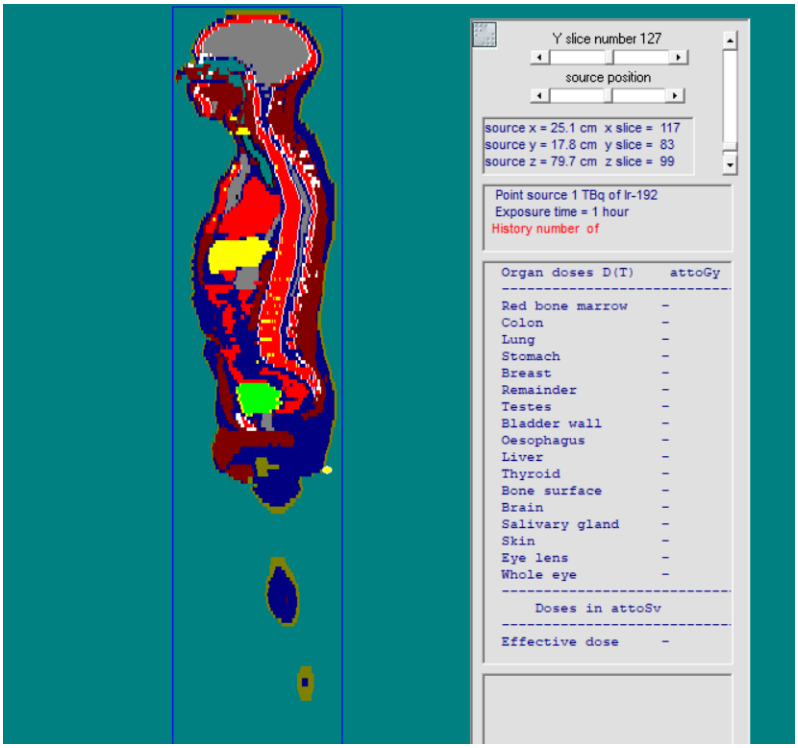

Figure 11. Source position from side view

Go to -> top view –> Local dose mode -> Turn on. The air in the phantom is colored white. This is because the slice chosen for viewing the local dose corresponds to the slice at which the source is positioned. This positioning is important as it is the voxels in this slice that will show the highest local dose. After around 500.000 histories, the button “See isodoses” produces the image shown in Figure 12.

A run of 10^7 histories takes around one hour with the graphics turned off and is sufficient to obtain a dose calculation with a low statistical uncertainty. The dose results are shown in scientific format by clicking Preferences → Dose results → Scientific format. The results are shown in Figure 12. In Figure 12 the voxels marked in black show areas where the equivalent dose is above 40 Gy. The voxels marked in yellow show areas where the equivalent dose is above 25 Gy but below 40 Gy. The yellow grid is set at 1 cm intervals. In this case, the black isodose limit is at a depth at around 2.5 cm from the skin surface closest to the source, and the outer yellow isodose limit is at around 3.5 cm from the same location.

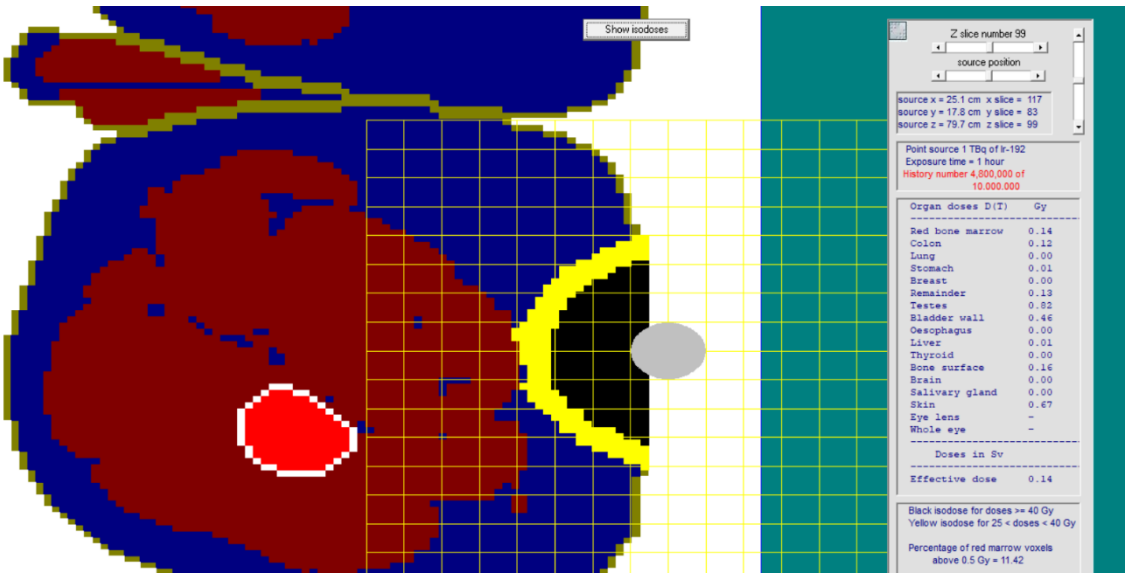

Figure 12. Isodoses in "local dose mode".

If you click with the left button of the mouse on the phantom tissue the red circle as shown in Figure 13 will appear:

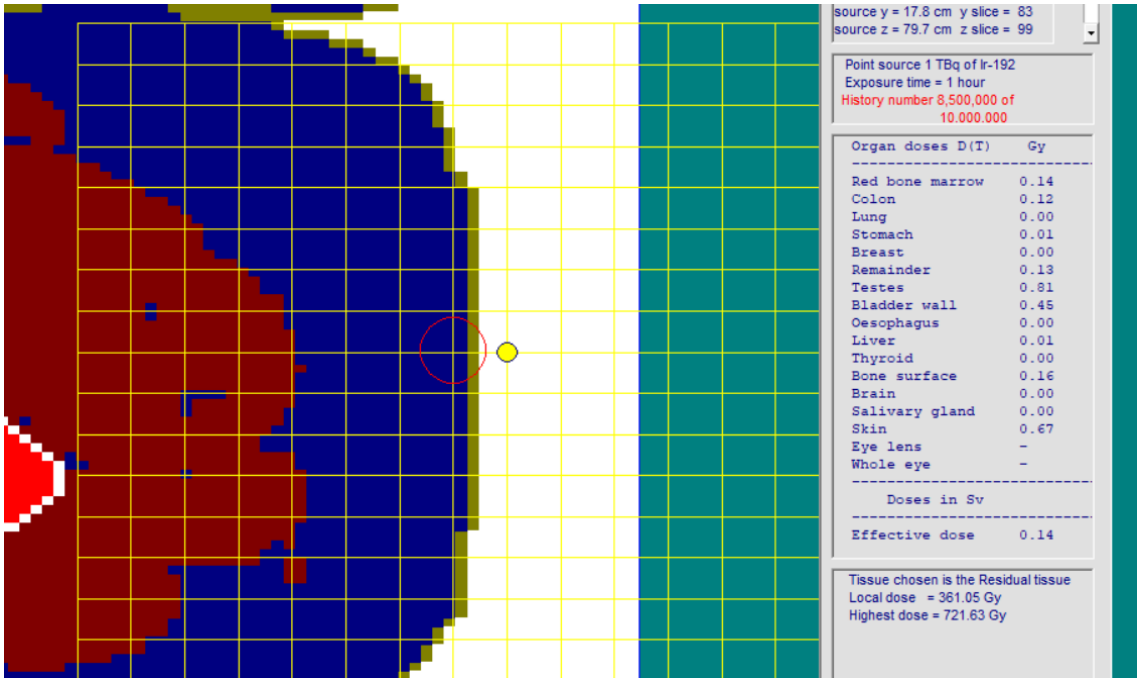

Figure 13. Visualizing the "local dose".

The dose reported in the lower information screen is the "local dose" or the dose calculated at the center of the red circle. In this case the dose at this point is estimated as 354 Gy, sufficient to produce a third-degree radiation burn to the skin near the source. By clicking on a number of points in the region near the source a map of the "local dose" can be made.

The visualization of the "local dose" can be made at any time during a run, but only after 10^6 histories will the calculated local doses start to "settle down" and become more reproducible.

3.7 Validation of point source dose calculations

There are a number of point source dose calculation programs available, some on-line. My favorite is the RADPRO calculator at http://www.radprocalculator.com/Gamma.aspx

In order to compare VMC dose calculations and those obtained through RADPRO it is necessary to use x = - 85 cm (because the "middle" of the phantom is around + 15 cm from the front of the phantom matrix that is positioned at x = 0 cm), y = 27.4 cm, (the middle of the male phantom looking at the front), and z = 120 cm more or less.

The RADPRO calculations are based on the inverse square of the distance method and should not be used if the source to phantom distance is less than around 50 cm. For distances less than 50 cm a Monte Carlo method such as VMC should be used. VMC can be used with the source in contact with the skin (or even inside the phantom).

VMC dc dose calculation has been extensively validated against results from physical phantoms with TLDs and against calculations made with other Monte Carlo programs, see References /1/ and /2/.

4. Ground and cloud source projects

In the case of a serious accident with extensive contamination of the ground and air, the dose to an adult exposed to the radionuclide on the ground or in the cloud can be calculated.

In VMC dc the geometry of the ground or cloud source is a room 300 m x 300 m x 150 m high with the phantom standing on the ground in the middle of the room. The photons are emitted at random on the ground surface (ground contamination) or in the air of the room (cloud contamination) and in the air voxels of the phantom. For the ground surface source the activity is in Bq/m^2 and for the cloud source the activity is in Bq/m^3.

If any other geometry is required, contact me at my email address.

4.1 Creating a ground surface contamination project

The ground surface source project parameters are established in a similar way to the point source project as in 3.2, see Figure 14.

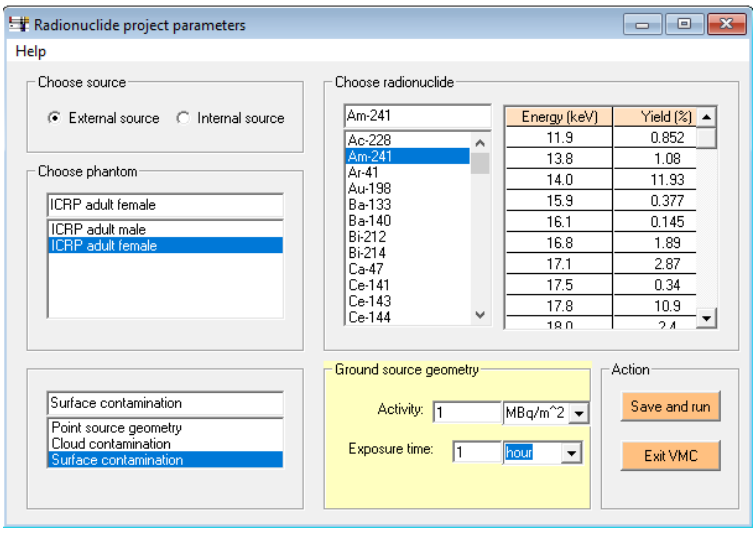

Figure 14. Ground surface project parameters, here a uniform ground surface contamination of 1 MBq/m^2 of ^{241}Am is assumed and the phantom is exposed for one hour.

4.2 Running a ground surface contamination project

VMC dc chooses a random position on the floor of the 300 m x 300 m "room", including the area directly underneath the phantom. The radionuclide at this position then emits the relevant photons in random directions and the photons are transported through the air of the room and ground surface. If the photon hits the voxel phantom matrix the photon is also transported through the matrix and the dose to the phantom tissue if any is recorded.

As the average radionuclide is located at a long distance from the phantom, at least 10^9 histories should be run to obtain reasonable tissue doses. The run of 10^9 histories with the graphics turned off requires around 4 hours of computer time. Two or three projects of VMC dc can be run at the same time on the same computer without slowing down the calculations. After around 10^8 histories a stable calculation of the effective dose will be obtained.

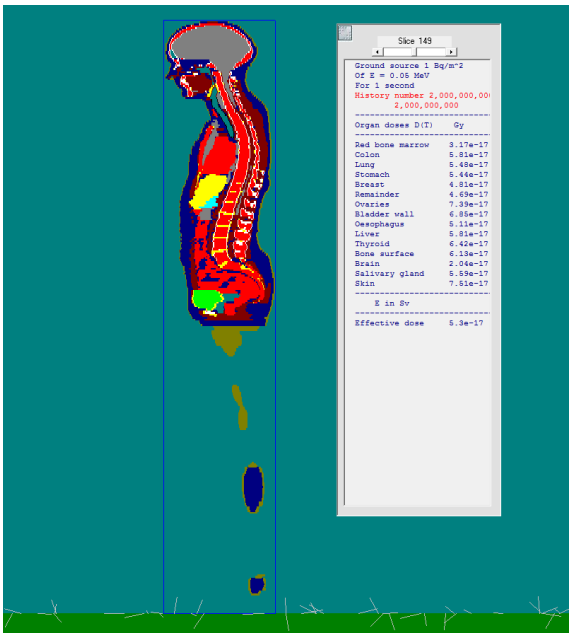

Figure 15. Female ICRP phantom exposed to 1 Bq/m^2 of photons of 50 keV for one second. The white lines on the ground indicate the start point and initial direction of the photons emitted.

4.3 Creating and running a cloud source contamination project

The cloud source project parameters are established in a similar way to the ground surface source project.

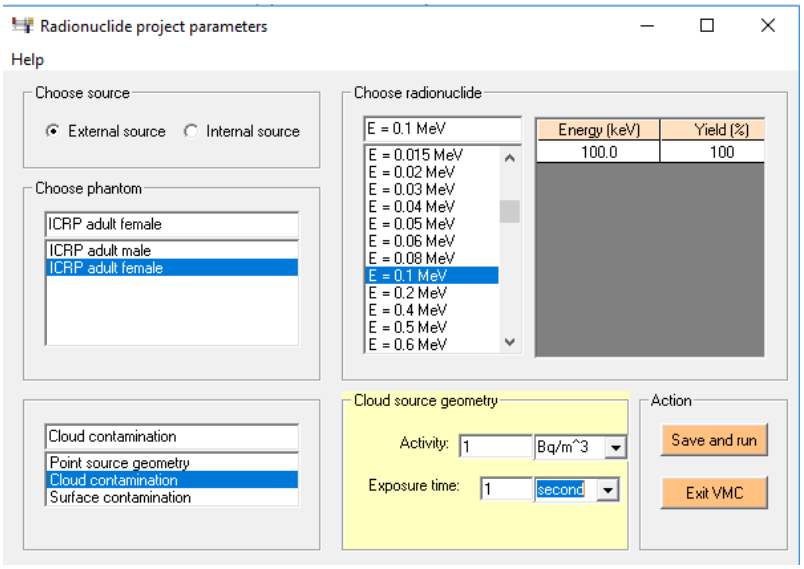

Figure 16. Cloud source project parameters, here a uniform cloud contamination of 1 Bq/m^3 of a radionuclide emitting 100 keV photons with a yield of one. The phantom is exposed for one second. The phantom graphics have been "zoomed out".

VMC dc chooses a random position in the "cloud" contained in the 300 m x 300 m x 150 m high "room", including the air voxels surrounding the phantom. The radionuclide at this position then emits the photons in random directions and the photons are transported through the air of the room and possibly are reflected by the ground surface and walls. If the photon hits the

voxel phantom matrix the photon is transported through the matrix and any dose to the phantom tissue is recorded.

As the average radionuclide is at a long distance from the phantom, at least 10^9 histories should be run to obtain reasonable tissue doses. Using the pop-up menu to zoom out once, the image produced after 2 x 10^9 histories, see Figure 17.

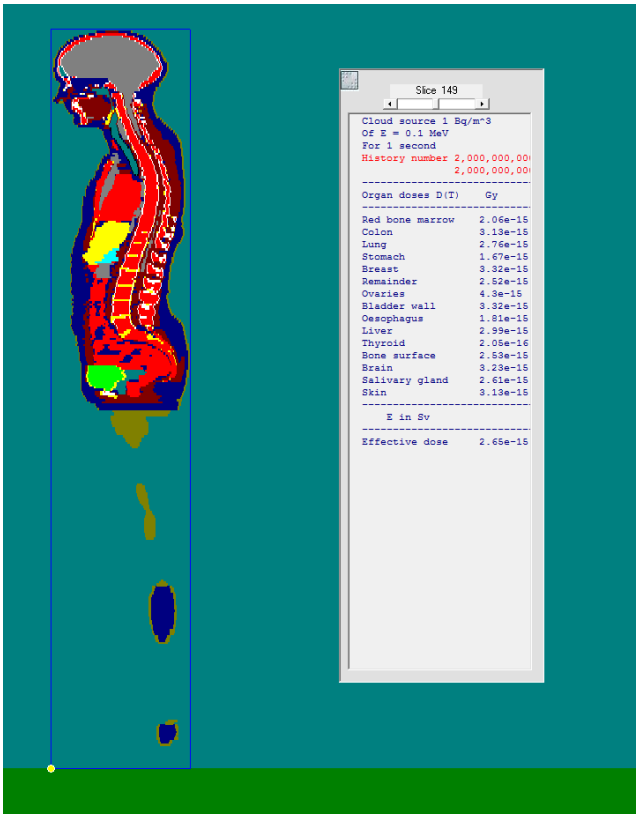

Figure 17. Female ICRP phantom exposed to 1 Bq/m^3 of photons of 100 keV for one second. The white lines in the air indicate the start point and initial direction of the photons emitted.

4.4 Validating ground surface and cloud contamination projects

Calculations of effective doses due to uniform ground or cloud contamination have been published, / 3/ and /4 /. VMC dc results are comparable to the FGR 12 results. For a ground source of 50 keV we have *E* = 4.5E-17 Sv per Bq s m^2 on page 23 of FGR 12. For a cloud source of 100 keV we have *E* = 4.0E-15 Sv per Bq s m^3 on page 25 of FGR 12.

5. Internal contamination

The internal contamination of a tissue or organ can be simulated. The radionuclide is uniformly distributed through the chosen organ. As VMC dc only transports photons, the dose to the

contaminated organ does not include the contribution of electrons emitted by the radionuclide. However, the doses to the other organs due to photons will be correct.

5.1 Starting and running an internal contamination project.

Choosing Radionuclide > New project the following screen will appear, see Figure 21. It is necessary to choose the button for "internal source", see Figure 18.

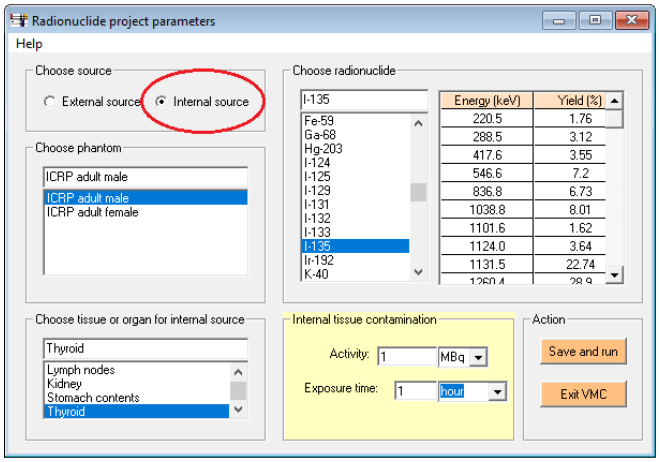

Figure 18. Opening project for male ICRP phantom with 1 MBq of ^{135}I in the thyroid for one hour.

After around 10^6 histories the doses to the other tissues should become stable, see Figure 19.

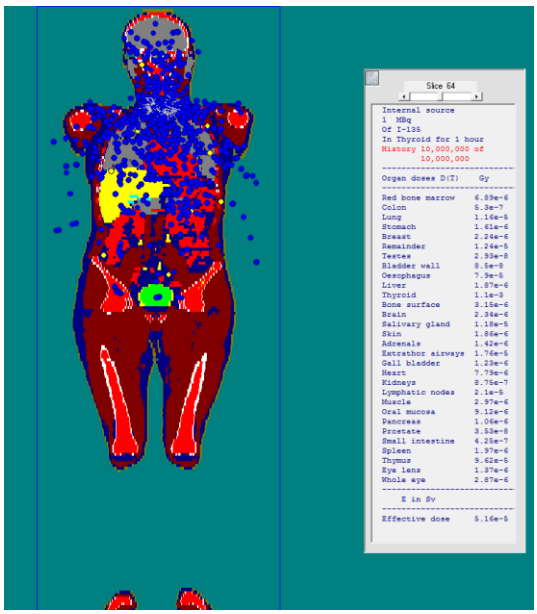

Figure 19. Male ICRP phantom with 1 MBq of ^{135}I in the thyroid for one hour, after 10^7 histories.

6. X ray projects

VMC dc allows the simulation of X ray exposures. It is possible to select a number of X ray spectra, select the collimator width and height, change the angle and position of the X ray beam and normalize the tissue doses to kerma area (Gy per Gy.m^2) or kerma in air (Gy per Gy). The geometry for the X ray exposure is a room 5 m x 5 m x 3 m height with the phantom placed in the middle of the floor. Photons that hit the phantom which are reflected from the ground and walls also contribute to the dose.

6.1 Starting the X ray project

With the "X rays" button chosen on the first page, choose whether to create a new project or to open an existing project file. If the button "new project" is chosen the following screen opens, see Figure 20.

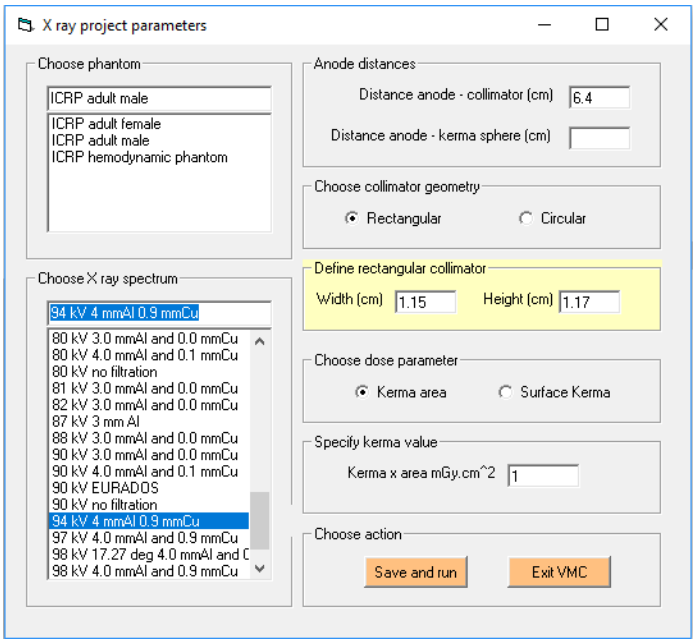

Figure 20. Define the new X ray project

6.2 Defining the project parameters

First choose the phantom. Available phantoms are the ICRP male, the ICRP female adult phantom and the "ICRP hemodynamic phantom". The "hemodynamic phantom" includes two male ICRP phantoms, one (the patient) lying on a surgical C-arm bed and the other (the doctor) standing beside the patient.

Figure 21. An example of a C-arm and surgical bed.

Secondly choose the X ray spectrum. The X-ray spectra were obtained using the software SpekCalc© Professional version /5/. An example of the spectrum generated for VMC dc by SpekCalc is shown in Figure 22.

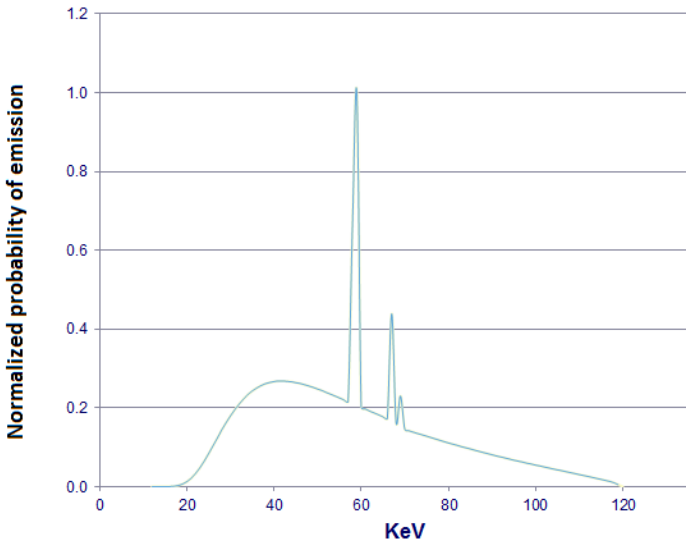

Figure 22. X ray spectrum generated by SpekCalc used in VMC dc. 120 kV with 3 mm Aluminium filter.

Define the distance anode – collimator (cm) and whether the collimator is rectangular or circular. Enter the relevant size (radius or width and height) of the collimator. If these distances are not specified in the manufacturer´s specification, these distances can be calculated by knowing the width and height of the X ray beam at a known distance from the anode, such as shown on a radiographic film or image intensifier. By performing a simple geometrical calculation the dimensions of the collimator at a given distance from the anode can be defined, see Figure 23.

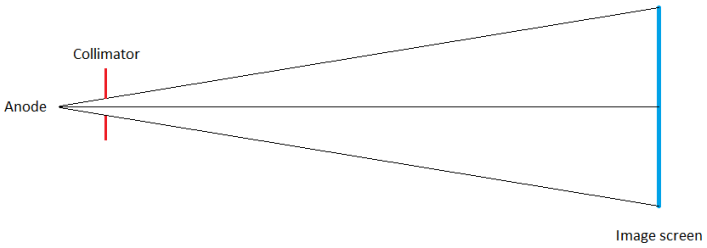

Figure 23. Geometrical configuration to determine the anode – collimator distance and the collimator dimensions.

6.3 Positioning the X ray tube

When the button "Save and run" is pushed, the following (zoomed out) image is seen, see Figure 24.

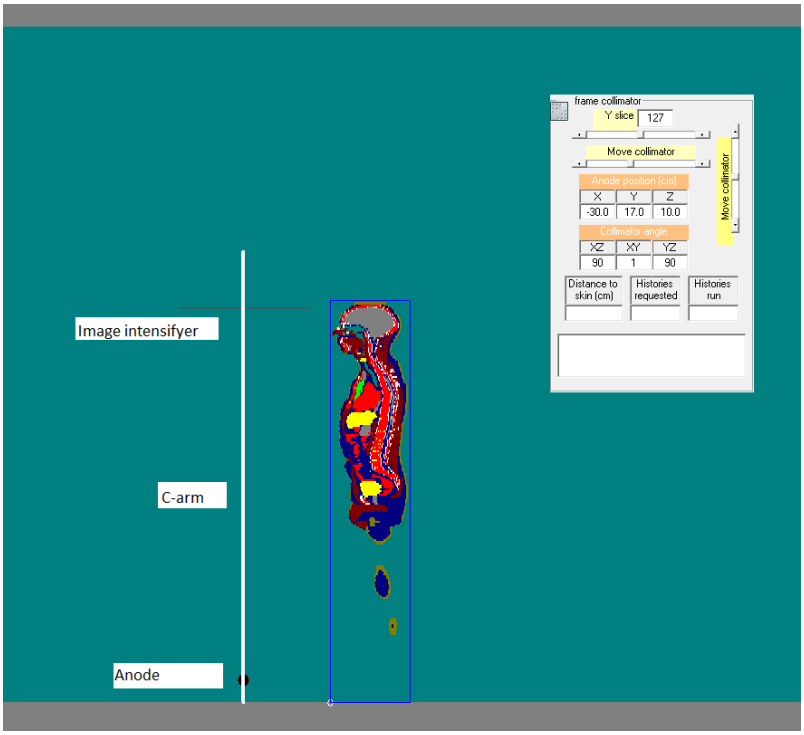

Figure 24. Opening screen of the X ray project showing the C-arm default position.

The C-arm can be moved to any position and angle by clicking on the horizontal or vertical move collimator bars. Also when looking at the side view, pushing the left key on the keyboard makes the anode rotate clockwise around the center of the C-arm. Pushing the right key on the keyboard makes the anode rotate anti-clockwise around the center of the C-arm, see Figure 25.

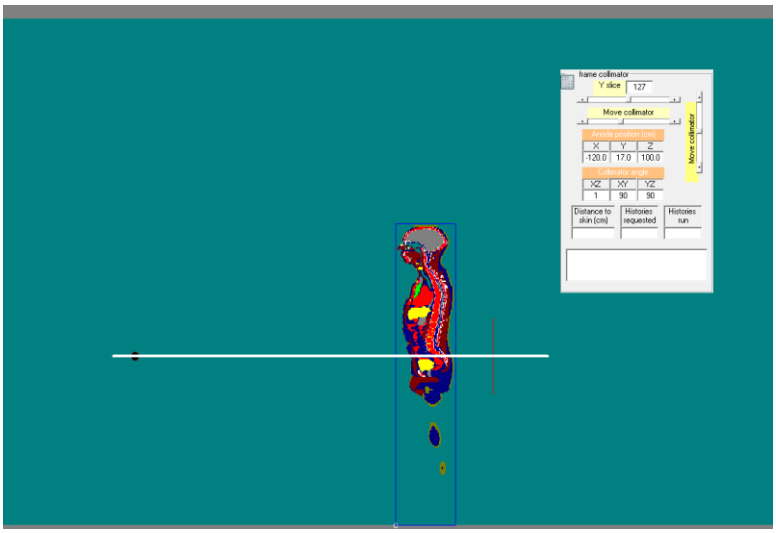

Figure 25. Looking at the side, pushing the left key rotates the C-arm to a horizontal position.

Looking at the front view, pushing the up key on the keyboard makes the anode rotate anti-clockwise around the center of the C-arm, pushing the down key on the keyboard makes the anode rotate anti-clockwise around the center of the C-arm, see Figure 26.

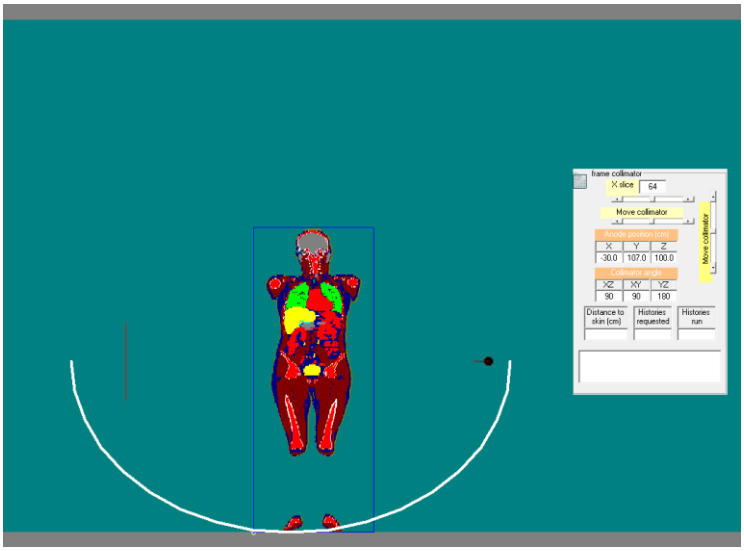

Figure 26. Looking at the front, pushing the up key rotates the C-arm to a horizontal position.

Looking at the side view, pushing the “A” or “Z” keys on the keyboard makes the C-arm rotate in the remaining plane, see Figure 27.

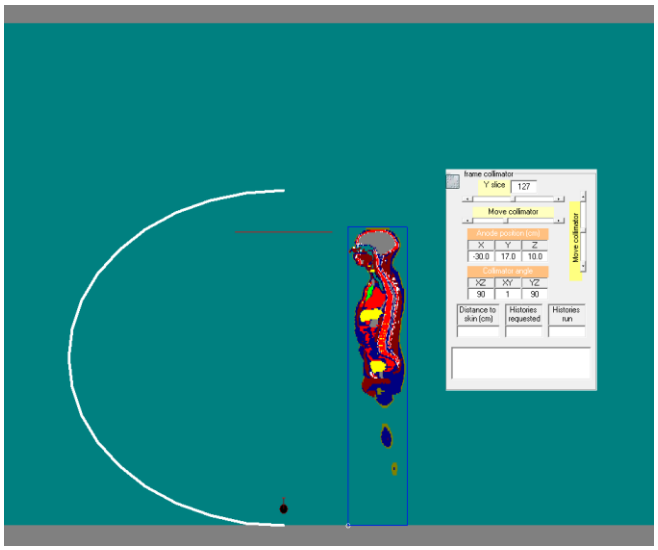

Figure 27. Looking at the side, pushing the "A" or "Z" keys rotates the C-arm around the remaining axis.

6.4 Running the X ray project.

In this example the X ray tube has been placed to simulate one of the 2018 EURADOS intercomparison exercises for dose calculation due to radiographic examinations, see Figure 28. The tissue dose results are saved to the project file. At least 10^9 histories are required.

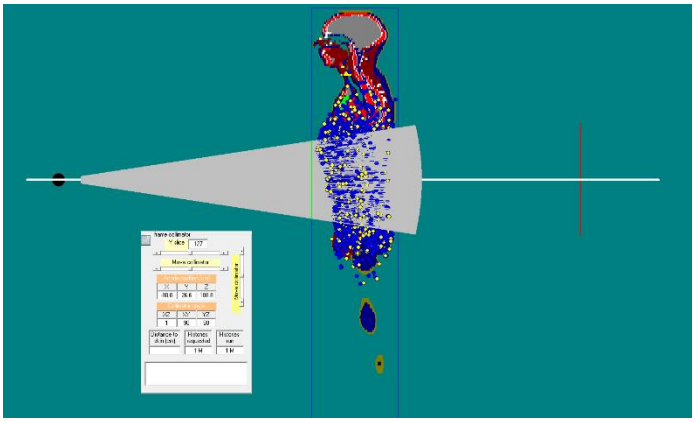

Figure 28. Simulation of a radiographic examination of the lower abdomen.

7. ICRP sources

This geometry is useful for confirming that the results obtained through VMC dc calculations conform to the dose coefficients given in ICRP publication 116 /6/.

7.1 Opening and running and ICRP source project

Choosing ICRP source and "new project" will open the following screen, see Figure 29.

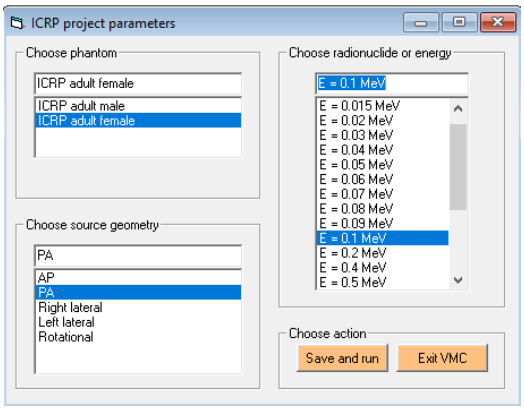

Figure 29. Opening an ICRP source project.

For the definitions of the ICRP geometry (AP, PA, etc.) see Figure 30.

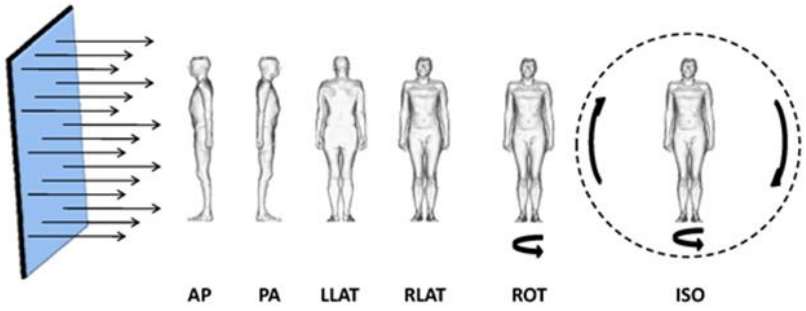

Figure 30. ICRP source irradiation geometries.

The resulting screen after running 10^6 histories is shown in Figure 31. In this case the photons are emitted randomly in a parallel beam from the back of the female ICRP phantom.

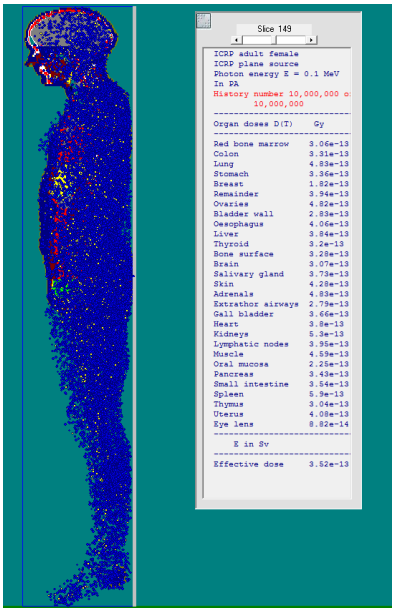

Figure 31. Female ICRP phantom irradiated PA. 10^7 histories.

7.2 Validating VMC dc results

The VMC dc tissue doses are given in Gy per unit photon fluence (Gy/cm^2) and can be compared with the ICRP 116 values. Comparing the two sets of results for the case shown in Figure 34 and Table 1 shows a good level of concordance. The results for bone surface and red bone marrow do show a 50% difference; this will be confirmed and corrected after the results of the 2018 EURADOS intercomparison are made available.

Table 1. Comparison of VMC dc and ICRP 116 dose coefficients.

Tissue	VMC dc coefficient (pGycm^{-2})	ICRP 116 coefficient (pGycm^{-2})	Ratio (%)
Liver	0.384	0.389	99
Uterus	0.408	0.424	96
Skin	0.428	0.429	99

8. References

/1/ Hunt, J. G., da Silva, F.C., Mauricio, C.L. The validation of Voxel phantoms and Monte Carlo methods applied to external irradiations. Radiation protection and Dosimetry, Vol 108, no. 1, pp. 85-89, 2004.

/2/ GOMES-ROS, J., HUNT, J. G. Monte Carlo modelling of Germanium detectors for the measurement of low energy photons in internal dosimetry: Results of an international comparison. Radiation Measurements. , v.43, p.510 - 515, 2008.

/3/ FGR 12 "External Exposure to Radionuclides in Air, Water, and Soil", 1993. Uses geometric phantoms https://www.epa.gov/sites/production/files/2015-05/documents/402-r-93-081.pdf

/4/ FGR 15 using ICRP reference phantoms (temporarily removed for correction from the US Environmental Protection Agency site) https://www.epa.gov/radiation/federal-guidance-report-15-external-exposure-radionuclides-air-water-and-soil

/5/ G Poludniowski, G Landry, F DeBlois, P M Evans and F Verhaegen. NOTE: SpekCalc: a program to calculate photon spectra from tungsten anode x-ray tubes. Phys. Med. Biol. 54 (2009) N433–N438 doi:10.1088/0031-9155/54/19/N01

/6/ ICRP, 2010. Conversion Coefficients for Radiological Protection Quantities for External Radiation Exposures. ICRP Publication 116, Ann. ICRP 40(2-5).

Annex I – VMC dose calculation specifications

A1.1 The mathematical phantoms

VMC dose calculation contains the ICRP male and female reference phantoms, for a detailed description of the phantoms, see ICRP, 2009. Adult Reference Computational Phantoms. ICRP Publication 110. Ann. ICRP 39 (2). I would like to acknowledge here the kind permission granted by the ICRP to distribute the two phantoms in this program. For copyright protection, the ICRP phantom files have been encrypted.

For the male phantom, a whole-body clinical computed tomography image set of a 38-year-old individual with height 176 cm and mass slightly below 70 kg (Reference Male: 176 cm and 73 kg) was selected for the construction of the male reference computational phantom. The person was lying supine with the arms parallel alongside the body. The data set consisted of 220 slices of 256 x 256 pixels. The voxel size is 8 mm in height with an in-plane resolution of 2.137 mm for the male.

The female reference computational phantom was based on the computed tomography scan of a 43-year-old individual with height 167 cm and mass 59 kg (Reference Female: 163 cm and 60 kg). The final data set consisted of 346 slices. The voxel size is 4.84 mm in height with an in-plane resolution of 1.775 mm.

AI.2 The Monte Carlo program and RANMAR

VMC is designed specifically for voxel geometries and has an extensive graphic output. It is written in Visual Basic version 6. As the energies of the radionuclides of interest for WBC laboratories fall in the range of 0.01 - 1.5 MeV, only photoelectric and Compton interactions are considered. The Monte Carlo code uses the RANMAR random number generator, with a period of approximately 10^{30} random numbers – more than sufficient for a dose calculation.