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Abstract

The human phantom IRINA, which is widely used for whole body counting calibrations, has been modelled using MATLAB. This document summarizes and explains the procedure that was applied for building voxel versions of IRINA in standing position. All 6 sizes in standing positions were successfully modelled with the help of MATLAB and the files are ready to use for any MC simulation. The MC code GATE was used to verify the geometry of the IRINA phantom by comparing the placement of source tubes and scatterers in the Monte Carlo model to the original IRINA documentation. The methodology can easily be used for building voxel phantoms of IRINA in sitting and bending position, as well as any other geometry that may be needed.

Key words

Voxel phantom, Monte Carlo simulations, Whole Body Counter, internal contamination, radiation dose

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1. Introduction

In case of a radiological accident it is important to act quickly in order to minimize the consequences of radionuclides released to persons and environment. For scenarios that involve the accidental contamination by radionuclides of humans, experimental data may be unavailable and emergency preparedness plays an important role in these rather rare incidents. Here, numerical simulations provide a useful tool to estimate the consequences of such an event. If, for example, a scenario involves internal contamination, it is convenient to be able to simulate the response of a detector, which in the case of internal contamination by radionuclides could be a Whole Body Counter (WBC). Readily available models may then help to take proper decisions in unusual and maybe chaotic situations.

With a WBC, it is possible to measure the total contamination of a person. However, isotope-specific calibration of the system is necessary for the correct evaluation of measurement data and can be achieved by experiment or Monte Carlo calculations. By applying both techniques, it is possible to validate calibration data towards each other and hence gain more confidence with WBC measurements in case of a real contamination incident.

The transport of ionizing particles in a medium and their subsequent energy deposition can be calculated with Monte Carlo (MC) codes for different purposes. In principal, all kinds of ionizing particles must be considered when modeling the interaction between radiation and human tissue, but the resulting radiation dose and subsequent biological damage vary strongly depending on:

- internal or external contamination;
- isotope and chemical properties;
- particle energy;
- tissue (weighing factors).

There are numerous MC codes that are used for simulating the transport of ionizing particles in different media, thus helping to estimate certain radiation effects. Codes like MCNP/MCNPX, GEANT4 or PENELOPE perform in a similar manner and need specific input files. Each code uses specific geometry definitions and it is of interest to provide a code-independent structure of the object to be modeled.

The aim of this project was to build a voxel phantom whose geometry file can be used in any MC code and to make it available through the NKS phantom library. The purpose of creating a simplified computational model of a human being is to simulate the spread of radionuclides in the body and to observe their dynamic distribution with respect to activity.

A **voxel** can be defined as a “volume-pixel” thus representing a certain value on a regular grid in a 3-dimensional space, see Fig. 1. Voxels are often used within medical imaging and data analysis. We will use the voxel notation to construct a human **phantom** which, in medicine and technology, is the simplified geometry of a biological object.

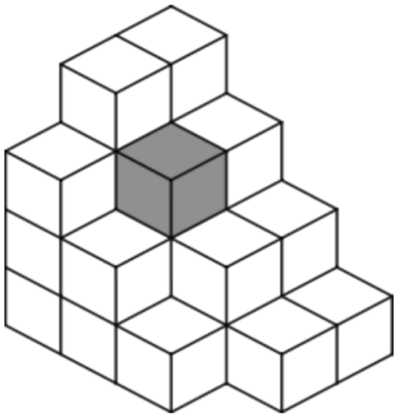

Figure 1. Stack of voxels of values 0 (white) and 1 (grey).

While it is common to use the solely numeric ICRP reference phantom (ICRP, 2009a) for simulating certain isotopic distributions in human tissue, we wanted to have the opportunity to combine numerical and experimental modeling. The human phantom **IRINA** (St. Petersburg Institute, 1996) is widely used for WBC calibrations and will be modeled in this work.

2. The IRINA phantom

IRINA is built up of a number of polyethylene (PE) blocks, in the continuation referred to as **scatterers**, that can be assembled into 6 differently sized humans (Tab. 1 and Fig. 2) in 3 different positions (standing, sitting, bending). The PE blocks come in two sizes - one is denoted **fully-sized** scatterer with a mass of 0.88 kg whereas the other one is approximately **half** as thick as the fully-sized one, weighing 0.4 kg. The maximum amount of fully-sized and half scatterers available for building an adult person is 90 and 40, respectively.

Table 1. Geometry parameters for different sizes of IRINA.

	amount PE blocks full-size / half	*assembled phantom mass [kg]*	*corresponding to human size*	*remarks*
P1	12	10.6	infant, 1 year, 12 kg	Tab.6 in IRINA documentation states P3-mass as 40.9 kg
P2	21/6	20.9	child, 6 years, 24 kg	
P3	36/28	42.9	teenager, 14 years, 50 kg	
P4	69/2	61.5	adult, 70 kg	
P5	72/36	77.8	adult, 90 kg	
P6	90/40	95.2	adult, 110 kg	

Each scatterer contains two empty channels, hereafter called **source tubes**, in which activity rods/sources can be placed. IRINA is delivered with three isotopes that come in sets of 90x2 "full-activity-rods" and 40x2 "half-activity-rods", cf. Tab. 2. Thus, there are totally 780 activity rods that can be used to achieve local to homogenous distributions of either Co-60, Cs-137, K-40 or combinations of those.

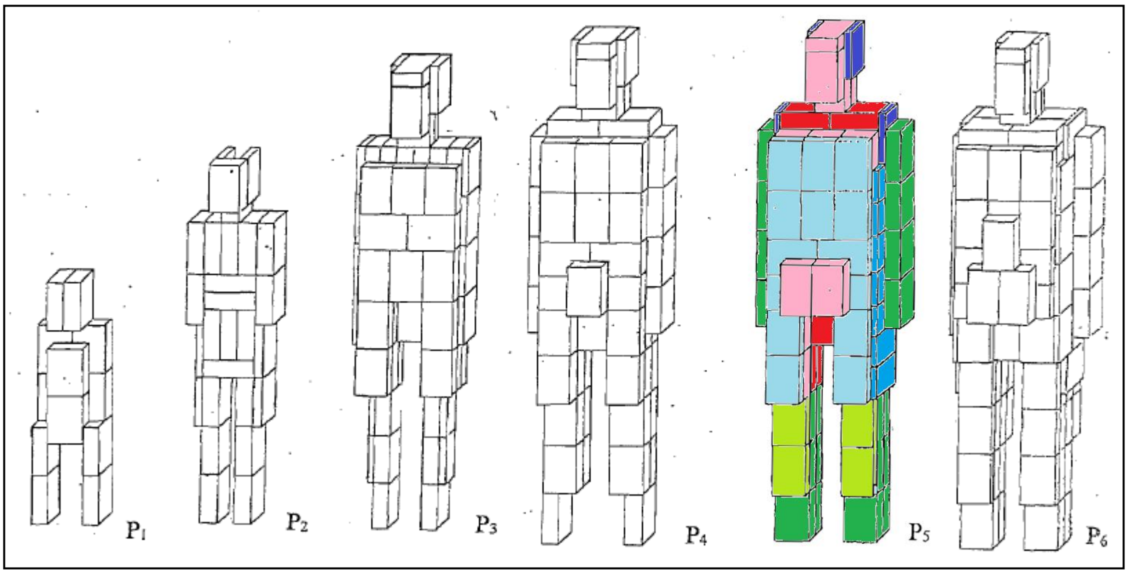

Figure 2. IRINA (standing) in 6 sizes according to Tab. 1.

Table 2. Specifications regarding cylindrical rod radionuclide sources.

	source number	*activity (1996-aug-01) [Bq]*	*half-life*	*measures*
Co-60	10.001 … 10.180	497	30.17 a	*Length:* 163 mm
	10.181 … 10.260	249		
Cs-137	30.001 … 30.180	242	5.272 a	
	30.181 … 30.260	121		*Diameter:* 6 mm
K-40	04.001 … 04.180	40.4	1.28e9 a	
	04.181 … 04.260	20		

To assemble the phantoms as presented in Fig. 2, the scatterers are joined by Al-pins, so-called **connectors**. A more detailed drawing of a fully-sized scatterer can be found in Fig. 3. A half scatterer differs from a fully-sized one only by its thickness which is 25 instead of 55 mm.

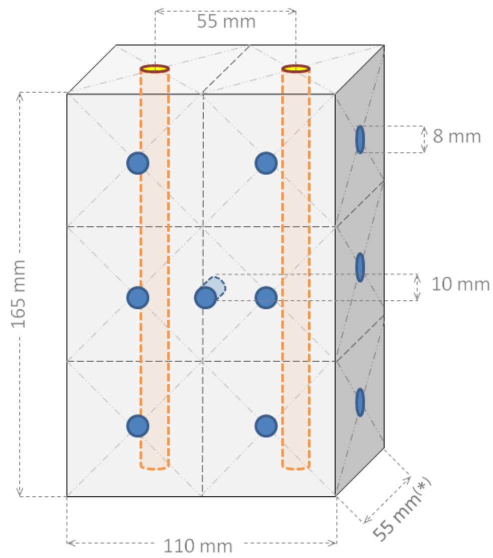

Figure 3. Drawing of a fully-sized scatterer. Half blocks have a thickness of 25 mm instead of 55 mm. Source tubes are presented by orange cylinders. The blue dots are connector-holes with a depth of approximately 10 mm.

3. Voxel Phantom

One of the required inputs for performing a MC calculation is a file that represents the geometry of the object to be simulated. MATLAB was used to build a generalized voxel model of IRINA where each entry of the resulting geometry file specifies a material identification (ID) number. In the following it will be explained how the most appropriate voxel size was determined and how to model the IRINA phantom.

General considerations

IRINA represents the simplified geometry of a human being by two types of scatterers. The measures of one fully-sized scatterer are related by 1:2:3 which means that the width is double and the height is triple its thickness. Therefore it may be considered that one fully-sized scatterer consists of 2 times 3 equally sized **unit cubes** with a side length of 55 mm, see Fig. 4. Each unit cube is then made up of several voxels whose size and thereby number per unit cube is determined by the maximum achievable resolution.

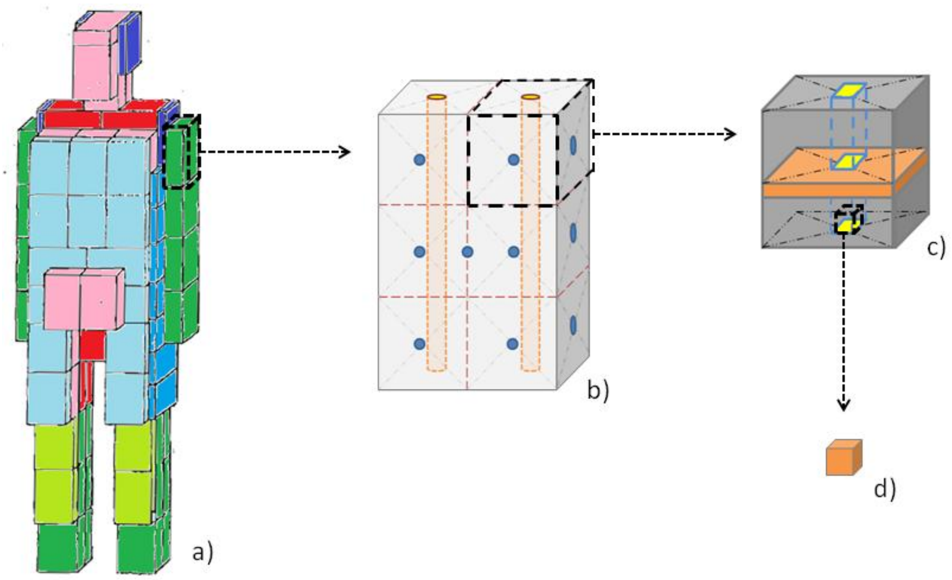

Figure 4. a) IRINA_P5 made up of, b) scatterers made up of, c) unit cubes made up of, d) voxels.

As a first step in building the voxel phantom, shape and size of one voxel were determined. Typically, voxels are cuboid and the maximum resolution that can be achieved with IRINA is on the order of the source tube's diameter, i.e. 8 mm.

If the diameter is used as voxel side length, its square area increases by ca. 30%. If the diameter instead serves as diagonal, the voxel side length becomes 6.1 mm, leading to a decrease in area by ca. 25 %, see Fig. 5. The voxel area is equal to the physical source tube area at a voxel side length of 7.1 mm.

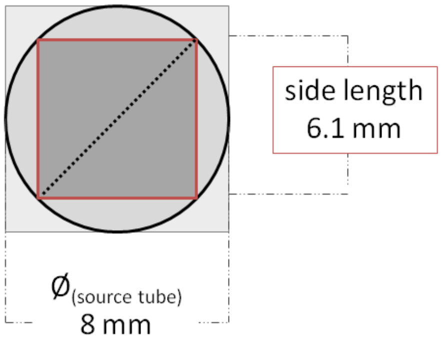

Figure 5. Determining voxel size.

The final choice regarding voxel size is a compromise between a scatterer's physical size and symmetry. With respect to the centric position of the source tubes, that means, for example, that an odd number of voxels is preferred.

Table 3. Defining scatterer in terms of voxels.

scatterer type	physical size [mm]	$number\ of\ voxels = \frac{\text{physical size}}{\text{voxel size}}$		
		voxel size = 6.1 mm	voxel size = 7.1 mm	voxel size = 7.9 mm
fully-sized	55	**9**.01	7.75	6.96
	110	**18**.03	15.49	13.92
	165	**27**.05	23.24	20.88
half	25	**4**.09	3.52	3.17

Tab. 3 lists the number of voxels per fully-sized scatterer for three different voxel sizes. However, only one candidate preserves both size and symmetry in a satisfactory manner:

- With a side length of 7.1 mm, symmetry is not achievable if one voxel is supposed to represent the centrally positioned source tube. The sizes of the scatterers are over-estimated.
- With a side length of 7.9 mm, perfect symmetry is achieved. The size of a fully-sized scatterer is over-estimated by 0.5 % whereas a half scatterer is 5 % smaller than in reality.
- With a side length of 6.1 mm, symmetry is achieved for the fully-sized scatterer and its size is slightly under-estimated (0.2 %). The half scatterer becomes asymmetric and 2 % smaller.

The thickness of two half scatterers joined together is smaller than that of a fully-sized one. The difference is 5 mm and should also be considered when choosing the most appropriate voxel size. Conclusively, a voxel side length of 6.1 mm is the best value.

In Fig. 3 it can be seen that there are connector-holes on three sides of each cube in addition to the source tube in the centre. Preliminary simulations of 0.1, 0.7 and 1.4 MeV gamma-particles passing through a single scatterer were performed. In order to investigate the necessary detail of a scatterer's geometry, two different cases were studied with the MC code GATE (version 6.2) (Jan et al., 2004; Jan et al., 2011). In the first case, all connector-holes were filled with air, in the second case, all were filled with PE. Even though connectors are made of Al, most connector-holes will remain empty when physically assembling IRINA. Therefore, the effect of Al was not regarded in the simulations.

Comparing the two cases, only a barely noticeable change in energy was observed after the gamma-particles had passed the scatterer, indicating that its geometry can be simplified. Hence, the connector-holes are excluded from the voxel phantom.

Modeling the phantom

With the known voxel size and simplified scatterer structure it is now time to actually build a voxel phantom that can be used as MC geometry input. There are certainly several approaches to do this and it was decided to use MATLAB for programming IRINA in a way that makes the phantom accessible to any MC code.

Defining IRINA in MATLAB is solved by transforming 3-dimensional into 2-dimensional space which is done by restructuring the phantom in form of slices. Here, one unit cube is made up of 9 slices such as shown in Fig. 6. Each slice of thickness 6.1 mm (voxel side length) has an area of 55x55 mm^2 rendering 9x9 voxels per slice. Thus, a fully-sized scatterer with a metric size of 55x110x165 mm^3 consists of 9x18x27 voxels in total.

All geometries except P1 contain half scatterers that need to be treated seperately. Fig. 6 also shows a smaller slice (9x4 voxels) in representation of such a half scatterer. With a physical thickness of 25 mm, the size of it translates to 4x18x27 voxels. Here, the source tube is positioned asymmetrically and the orientation of a half scatterer is chosen so that the thicker PE layer is on the outside of the phantom.

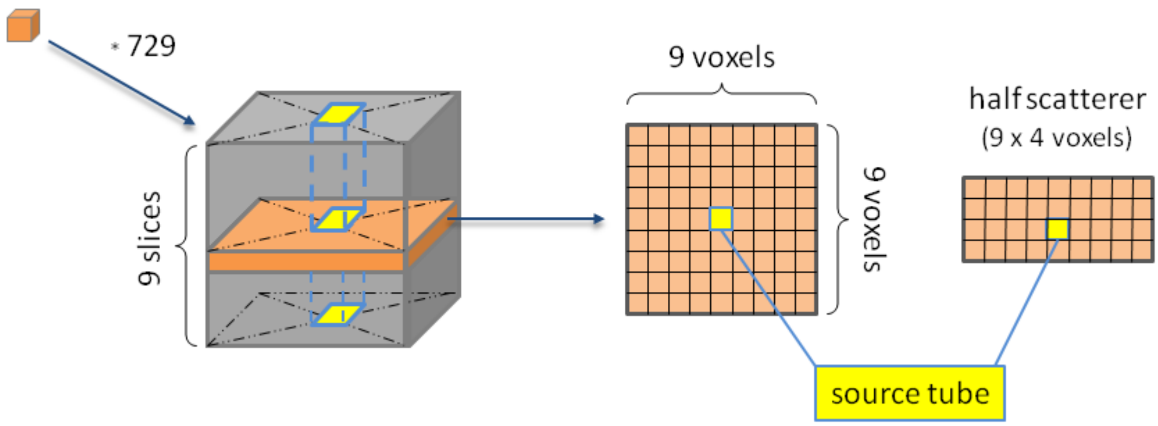

Figure 6. Sketch of how to build a unit cube, used to compose a fully-sized scatterer. 729 voxels build one cube: 9 slices à 9x9 voxels. No connector-holes; only *square* source tube in the middle. (One slice of a half scatterer with 9x4 voxels with central source tube in the third row.)

In MATLAB, a two-dimensional slice is easily expressed in form of a matrix, where each entry defines the material property of a voxel. The entries in the matrix are material identification numbers (material ID) where each number links to the physical and chemical properties of the material.

If “1” is the material identification number for PE and “X“ the material ID for the source tube, then the matrix form of one slice of the unit cube in Fig 6. becomes:

```
1   1   1   1   1   1   1   1   1
1   1   1   1   1   1   1   1   1
1   1   1   1   1   1   1   1   1
1   1   1   1   1   1   1   1   1
1   1   1   1   x   1   1   1   1
1   1   1   1   1   1   1   1   1
1   1   1   1   1   1   1   1   1
1   1   1   1   1   1   1   1   1
1   1   1   1   1   1   1   1   1
```

Instead of creating a MATLAB array of nine such matrices that make up a unit cube, it was chosen to represent each slice in vector-form. Hence, the matrix above was transformed into a vector by putting row after row so that nine similar vectors build $^1/_6$ of an IRINA scatterer, see. Fig. 4.

The approach of using matrices that specify slices is also used when building a complete voxel version of IRINA in any size. Here, it is imagined that the phantom stands on a grid whose size is determined in terms of unit cubes. The maximum occupied surface of the standing phantom (P1 to P6) is found in the abdomen-region and the grid dimensions are determined by simply counting the amount of virtual cubes in x- and y-direction, see Tab. 4 and Fig. 7.

For P1, P2 and P4, each grid is of size 9x9. If occupied by a unit cube the grid is filled with ones and a specific material ID at the position of the source tube. An empty grid is filled with zeros. For P3, P5 and P6 several half scatterers are used to build IRINA, cf. Fig. 2. Here, the grid structure is adjusted to fit the position of half scatterers and affected grids are sized 9x4, represented in Tab. 4 by the addition of 1 or 2 such “half grids”, depending on the phantom size. An example of such a grid structure is given by Fig. 8 (red arrows).

Table 4. Grid measures in terms of unit cubes.

grid size	*x*	*y*	*z*
P1	4	2	15
P2	5	3	22
P3	6 + 2	3	29
P4	8	4	31
P5	8 + 2	4 + 1	31
P6	8 + 2	5 + 1	31

When programming the voxel phantom, it is important to know the correct position of geometry read-in since it probably varies with respect to the chosen MC code. In the txt-file of the standing IRINA phantoms we followed the same structure as the ICRPs voxel phantom and the description of the array are taken from the description of ICRP (ICRP, 2009b). The material IDs “are listed slice by slice, within each slice row by row, within each row column by column. That means, the column index changes fastest, then the row index, then the slice index. Slice numbers increase from the toes up to the vertex of the body; row numbers increase from front to back; and column numbers increase from right to left side” (ICRP, 2009b).

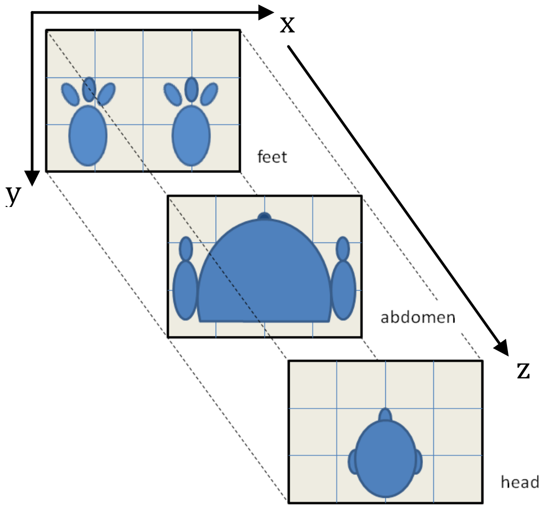

Figure 7. Slices of imaginary phantom to count the amount of occupied grid fields.

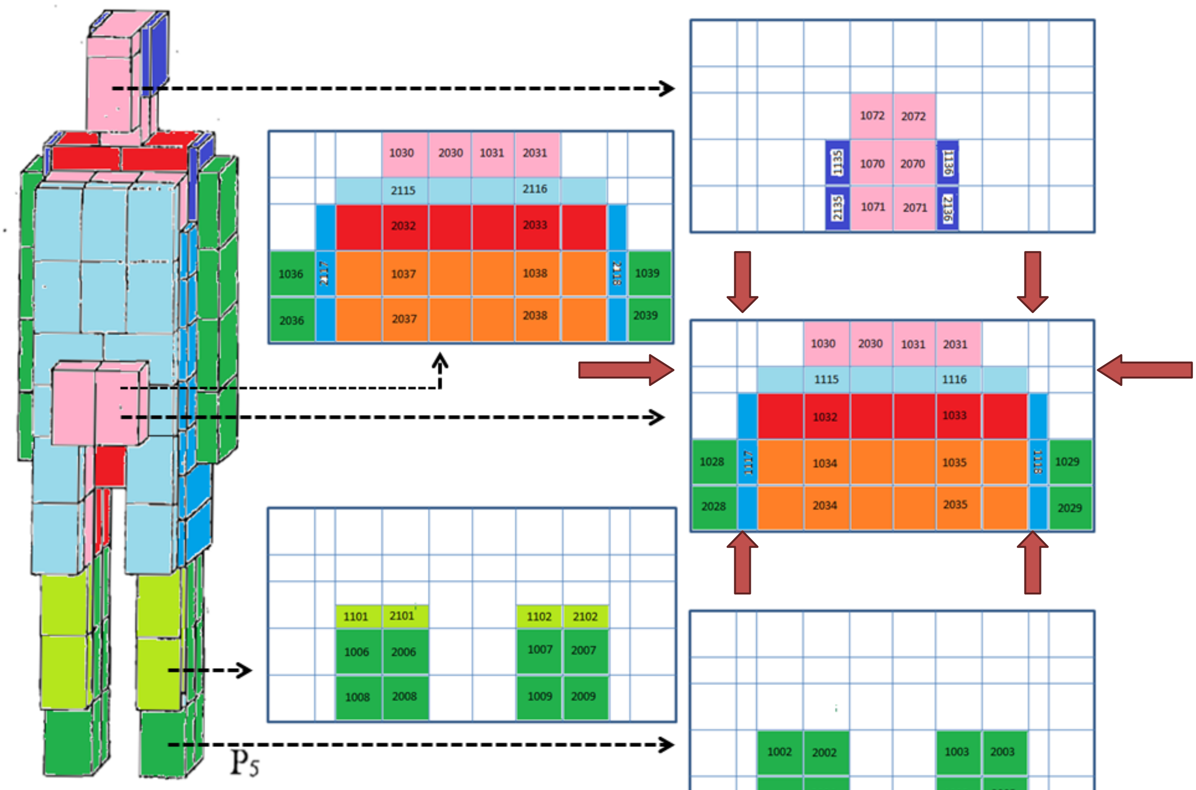

Figure 8. Demonstration of certain P5 slices in grid structure.

Apart from the difficulties arising from the presence of half scatterers, two more things have to be regarded carefully when modeling the different sizes of IRINA:

- not only each scatterer but also each source tube should carry a material identification number according to its position;
- all geometries except P1 have at least one source tube in x- or y-direction (horizontal) leading to a non-repetitiveness of affected slices.

Each fully-sized scatterer contains two source tubes that are enumerated by **10X** and **20X** with X ranging from **02 to 91**. The source tubes of half scatterers are enumerated by **11Y** and **21Y** with Y ranging from **01 to 40**.

The occurrence of horizontal source tubes is of concern if voxel phantoms of IRINA in other geometries (sitting or bending) are to be created since here the usual repetitiveness of vertical slices is broken. In MATLAB, the phantom is not build by explicitly writing down each slice in matrix form. All matrices belonging to a vertically positioned scatterer are repeated at least 9 times (height of a unit cube) and only the source tube number has to be changed. If, on the other hand, the orientation of the scatterer changes to horizontal it becomes necessary to define and insert explicit matrices. This procedure is most challenging for size P5 but is rather effective with respect to the readability of the MATLAB code.

4. Results and conclusions

This document summarizes and explains the procedure that was applied for building voxel versions of IRINA in standing position. All 6 sizes in standing positions were successfully modelled with the help of MATLAB and the files are ready to use for any MC simulation. The MC code GATE was used to verify the geometry of the IRINA phantom by comparing the placement of source tubes and scatterers in the MC model to the original IRINA documentation. The methodology can easily be used for building voxel phantoms of IRINA in sitting and bending position as well as any other geometry that may be accomplished.

The experimental parts that are valuable for validity studies such as mentioned above will be made in future works.

The mapping over material IDs according to each size of IRINA can be found in the appendix. In Fig. 9, all material IDs in P5 along the xz-plane of the grid's 2nd row are presented, cf. Fig. 8. All are half scatterers (light blue) with their source tubes marked by solid bold lines in white and purple (color coding only for purpose of readability).

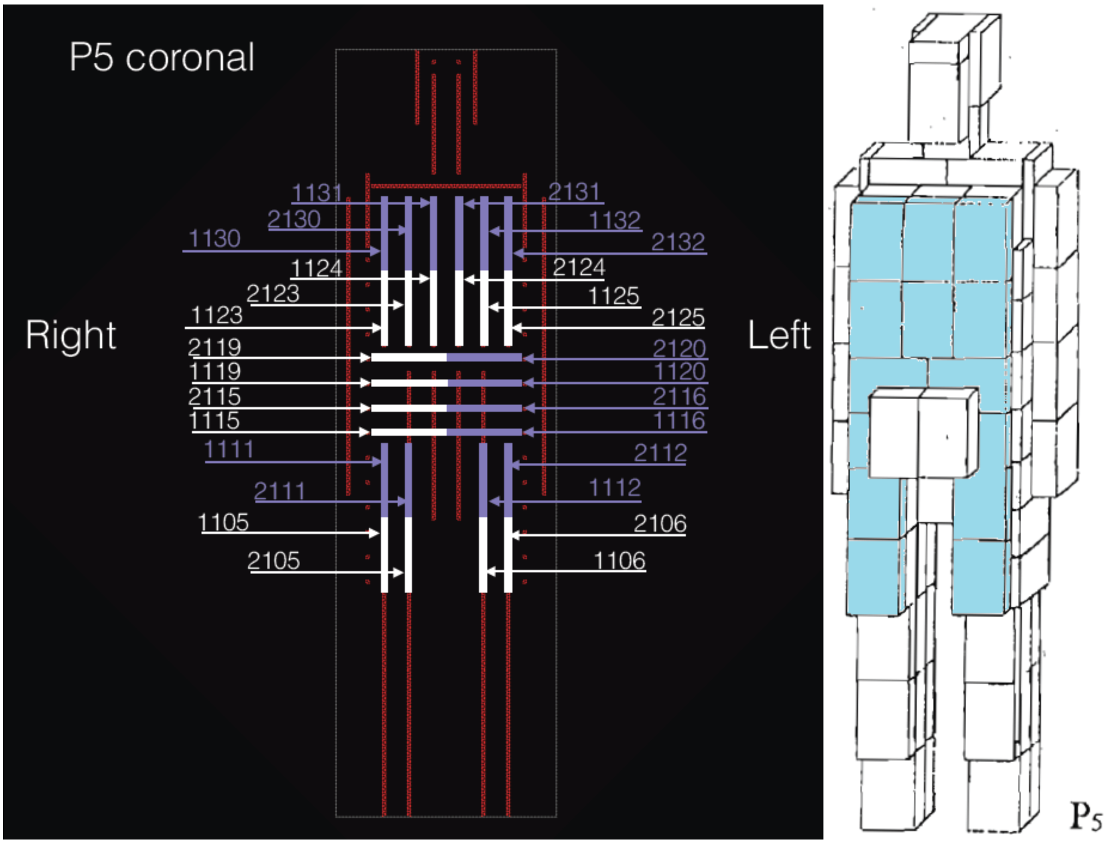

Figure 9: Excerpt from file "P5.pdf" (pg. 3) to demonstrate material ID mapping of scatterers in 2nd y-plane.

5. Acknowledgements

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6. Disclaimer

The views expressed in this document remain the responsibility of the author(s) and do not necessarily reflect those of NKS. In particular, neither NKS nor any other organisation or body supporting NKS activities can be held responsible for the material presented in this report.

7. References

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Jan et al, 2011. *GATE V6: a major enhancement of the GATE simulation platform enabling modelling of CT and radiotherapy*, Phys. Med. Biol. 56 (4) 881.

8. Appendix

The voxel phantoms come as txt-files, named according to size and geometry:
P1_voxel_lyingIRINA.txt
P2_voxel_lyingIRINA.txt
P3_voxel_lyingIRINA.txt
P4_voxel_lyingIRINA.txt
P5_voxel_lyingIRINA.txt
P6_voxel_lyingIRINA.txt

Maps over material IDs are found in the form of pdf-files:
P1_IDs_lyingIRINA.pdf
P2_IDs_lyingIRINA.pdf
P3_IDs_lyingIRINA.pdf
P4_IDs_lyingIRINA.pdf
P5_IDs_lyingIRINA.pdf
P6_IDs_lyingIRINA.pdf

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