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Technical note

# Calculating equivalent dose received from a patient undergoing nuclear medicine procedure by merge phantoms tool and GAMOS/Geant4 6.0.0 software

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ABSTRACT

*Purpose:* This report introduces a tool for merging two voxel phantoms to calculate the deposited dose that a person receives from a patient undergoing Nuclear medicine procedures.
*Materials and methods:* The phantoms must be converted to the text format used by GEANT4 to treat DICOM images via the GAMOS utilities. The Merge Phantoms Tool can merge two phantoms in two different cases: standing either side by side or opposite. The merged phantom is also in text format and is subsequently input back into GAMOS to calculate the equivalent dose that a person receives from a patient. The equivalent doses to the eyes of people in contact are calculated in a case where a patient was administered 185 MBq of 18F-FDG during a PET examination.
*Results:* The corresponding doses when the two phantoms are standing opposite are greater than those when they are standing side by side and smaller than those from point and tube source calculated by Sumi Yokoyama at any distance.
*Conclusions:* The Merge phantoms tool and GAMOS software can be used to calculate the deposited dose that a person receives from a patient. An accurate dose calculation can be used for radiation protection, or deciding whether a patient can be released from isolation if the dose is small even in a close contact.

## 1. Introduction

Nuclear medicine (NM) is known as a weapon to fight against cancer. Despite its many benefits, this procedure also brings about various health risks for people who are exposed to radiation. Patients undergoing NM investigation may become radioactive sources for people who are in close contact with them [1]. Staff, the caregivers, family members or members of the public (fellow travelers, bus and taxi drivers) can also get irradiated from patients. Therefore, radiation protection is a major issue in NM. The dose limits and isolation for each circumstance have to be considered carefully. Doses for the hand, finger and skin are focused on for the workers who are responsible for procedures which require the handling of radiopharmaceuticals in contact or very close to the extremities. The distance between patients is recommend to be extended and they should use private instead of public transport [2]. According to a research conducted by V. Morán et al with 194 patients [3], during the radiopharmaceutical incorporation, someone who is present in the same waiting room with an injected patient may receive up to 0.59 mSv. If the patient had a medical appointment, or went to a restaurant or a coffee shop, members of the public could receive 23, 43, and 22 µSv, respectively [3]. There is no need for total physical isolation, patients can freely hug or even have sex with their partner on condition that the total duration of contact is less than half an hour per day. However, sleeping alone is strongly advised, with a distance of at least 2 m from their partner [4]. In the study by John M.H. de Klerk [5], from the patient treated with I-131, the cumulate annual dose that a nurse receives for one week after treatment is 6.3 mSv if the patient is completely incapable of self-care. Without any restrictions, the cumulative annual dose can be up to 103 mSv for partner and 132 mSv for children under 2 years old (administered dose of 7400 MBq $^{131}$I in ablation patients).

We can see that the dose received from a patient undergoing NM procedures in general can be very diverse, depending on the condition of contact (duration, distance…) and the condition of the patient

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(activity or density distribution). If a patient has a rather more peculiar condition compared to others, such as an unusually large thyroid remnant, or hyperthyroid patients with significant uptake, more severe restrictions will be required. Moreover, if the recipients are pregnant women, infants or weedy people, the dose received from these patients could pose a serious threat to them. Female patients with young children are especially concerned about radiation and often wish to know the potential dose their children could receive.

But in some cases, isolation is difficult to be implemented. For example, a patient who is incapable of self-sustaining or parents who need to take special cares of their children. There are also cases where the isolation seems to disturb the patients, making them feel depressed or uncomfortable. In recent years, an increasing number of patient-centered improvements have been made, especially to Nuclear medicine inpatient units. Friederike et al studied the fear of isolation in patients who are treated with radioiodine [6]. The result indicates that thirty percent of the patients have major problems with isolation. The others do not feel too much discomfort as long as they have television, internet and other facilities [6]. On the other hand, in developing countries, investing in divertissement for patients is still rather challenging. Therefore, if there are sufficient evidences showing that the dose which a person receives from a patient is small even in close contact and without any restrictions, undue anxiety can be reduced. Patients should be released from isolation so that they can overcome their psychological problems and be better taken care of [7]. To protect people who come into contact with patients as well as release a patient from isolation, a rigid method to calculate the accurate dose to the contacting people is required.

To simplify the dose calculation, in many researches, the activity in such patients is generally assumed to be an unattenuated point source regardless of the density and activity distribution in the body of the patient and the dose to exposed individuals at a given distance is therefore calculated using the inverse square law [8]. This assumption may overestimate of the dose, such as in the case of palliative treatment. Dejan Zˇontar pointed out that, "V*arious authors assessed accuracy of dose calculation models by comparing calculated doses with actual measurements and a simple point-source model significantly overestimates dose rate at short distances"* [2]. Siegel JA et al. proposed a line-source model with attenuation correction [8]. They supposed that there are more accurate models but limit their study to the line-source approximation. In a study by Palmer [9], an "Excel-based system" is used to manage radiation safety for the family of patients undergoing I-131 therapy. In this study, the extrathyroidal component was a cylindric volume with a diameter corresponding to the patient's size, whereas the thyroidal component was a point source. The workbook system permits selection of appropriate dose limits for each individual [9]. The system was organized into a set of 4 workbooks with specialized features. However, the workbooks were only developed for radiation protection procedures for the family of patients undergoing I-131 therapy. This raises concern that the workbooks may underestimate the dose to a child held by the patient. According to Palmer [9], in a worst-case scenario, the dose for a held-child may increase up to 13.4%. The tools using source models instead of patient-source have limitations on geometry as well as scope of application. There are several Monte Carlo simulation software which can compute the accurate absorbed dose for a patient using their CT image. However, in order to calculate the dose that a person receives from a patient, we need a tool which is able to include two voxel phantoms of both the patient and the contacting person at the same time, which is still not a great deal of consideration in available dose software. In this report, we propose a method to calculate the deposited dose that a person absorbs from a patient who has used radiopharmaceuticals, using two voxel CT phantoms through our "Merge Phantoms Tool" (MPT) and GAMOS 6.0.0 software [10,11]. This method is applied to calculate the doses to the eyes of a person who has been exposed to a patient using $^{18}$F-FDG when the distance from the person to the patient is 10, 20 or 30 cm. The Adult Male Reference Computational Phantoms (the AM phantom) presents the contacting people [12]. The PET and CT images of the patient are in DICOM format. The equivalent doses per minute to the eyes are calculated in two cases: the two phantoms are standing opposite to each other and side by side when the patient was administered 185 MBq of $^{18}$F-FDG during a PET examination. The doses per minute from a source of 1 MBq for opposite phantoms are then compared with the corresponding dose calculated by Sumi Yokoyama et al for point and tube sources [13]. The calculations in this study are intended for illustrating our MPT and GAMOS software, which can be used to estimate the deposited dose that a person receives from a patient easily.

## 2. Materials and methods

### 2.1. Merging two phantoms

From version 5.1.0, GAMOS can read CT images to calculate absorbed dose at voxel level. Based on top of the Geant4 platform, GAMOS allows users to implement the dose calculation with command lines. Users need to simulate the source and the phantom. If the phantom is CT image, it has to be converted to text file (g4dcm file) before starting the calculation. With the version 6.0.0, GAMOS can deal with any NM image, but read only one voxel phantom in a simulation. It can help to calculate the internal dose to a patient using pharmaceutical. To calculate the dose that a healthy person receives from the patient, both CT phantoms have to be included. This feature, however, is not yet supported by GAMOS. Therefore, we merge two phantoms into a single phantom in the text format of GAMOS, so-called "merged phantom", in order to solve this problem.

The merged phantom is a box containing two CT phantoms. The voxel dimension in the merged phantom is equal to that of the AM phantom (2.137 mm × 2.137 mm × 8 mm). The AM phantom comes with the list of materials indices for each voxel, plus a file detailing the composition of all materials used. The merged phantom is created for a given distance between the two phantoms using the list of ICRP materials of the ICRP 110 publication. The coordinates of each voxel of the merged phantom are used to know its relative position in the two phantoms. This information, together with the original data of each phantom in the text file, determines the material and density of each voxel. "Merged phantom" is created in two cases. In the first case, a person and a patient stand opposite to each other. The second case occurs when the two phantoms lay or stand side by side, provided that the distance between them is 10, 20 or 30 cm.

- Standing opposite

We assume the two phantoms are standing opposite, face to face. The coordinates of the two phantoms has the following relation: On the × axis, $x_{min}$ and $x_{max}$ of each phantom are symmetrical across the origin. On the z axis, the minimum limit of the two phantoms are equal. On the y axis, the AM phantom moves so that it makes a distance to the patient. To make the two phantoms stand face to face, we rotate the AM phantom by 180 degrees.

- Standing side by side

The two people lay on their back or stand side by side. The y coordinates of the two phantoms are kept so that $y_{min}$ and $y_{max}$ of each phantom are symmetrical with respect to the origin. On the z axis, the minimum limit of the two phantoms are equal. On the x axis, AM phantom move so that it makes a given distance to the other. No rotation is needed in this case.

In both cases, if the CT image of the patient is missing a part of the legs, on the z axis, the phantom merging bases on the actual height of the AM phantom and the patient to find the positions of their vertexes.

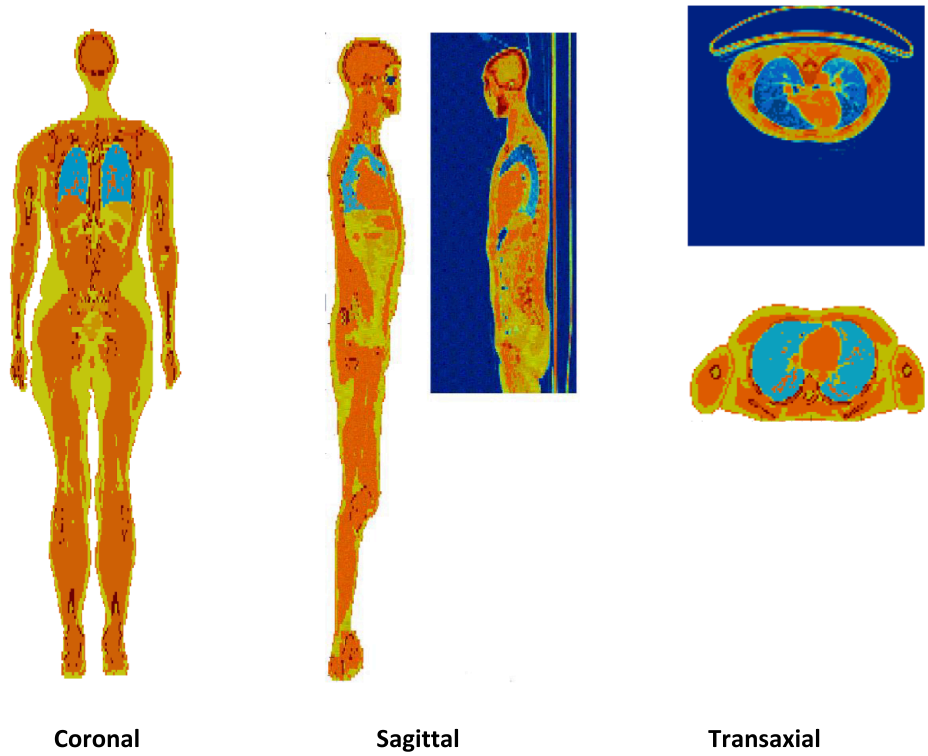


**Fig. 1.** The “Opposite phantom”.

### *2.2. Writing the merged phantom in text format of GAMOS*

To calculate the deposited dose using GAMOS, information about merged phantom has to be converted to a simple ASCII format [14]. Users may also create these files manually with the following format:

Number of materials
Name of the materials
Number of voxels on x, y and z axes
Minimum and maximum extension in x, y and z coordinates
$N_x$ X $N_y$ X $N_z$ material indices
$N_x$ X $N_y$ X $N_z$ material densities
$N_x$ X $N_y$ X $N_z$ structure indices
Structure names

After merging the patient and the AM phantom into merged phantom in a distance, we can check this task by observing the merged phantom from any region using the DICOM visualization utility of GAMOS.

### *2.3. Using “Merge phantoms” tool*

With a simple interface, our tool allows user to merge two voxel phantoms without requiring neither special effort on operation nor certain knowledge of programing and ASCII code. Users only need to convert the CT image from DICOM format into text format with the assistance of GAMOS software. Then input the location of the two text files to MPT. Thereafter, the space between the two phantoms is instructed to be input in the unit of cm. When process of merging phantoms is finished, the merged phantom will be placed in the same folder as the other two phantoms. Our tool also has utilities for separating material index value, or density, or structure index. After extracting these values, users can use the GAMOS visualization utility to visualize the merged phantom in all three planes, with the possibility of “zooming” any region of interest. To assess the deposited dose received by a healthy person from a radioactive patient, we use the PET/CT images of a male patient (weight: 75.0 kg, height: 172 cm) and the AM phantom (weight: 73.0 kg, height: 176 cm) to represent a healthy person. The voxel sizes of the CT and PET images of the patient are (0.977 mm × 0.977 mm × 2 mm) and (4.072 mm × 4.072 mm × 3 mm). The CT and PET image datasets consist of 512 × 512 × 486 and 168 × 168 × 324 voxels. The following phantoms are the “Merged phantom” of AM phantom and the CT image of the patient (Fig. 1 for “Opposite phantoms” and Fig. 2 for “Side by side phantoms”).

The patient was administered 185 MBq of $^{18}$F-FDG during a PET examination. The PET DICOM image can be read by GAMOS to generate the isotope activity proportional to each voxel activity in the image. The reconstruction uses an OSEM algorithm, with 8 subsets and 4 iterations, a Gaussian filter of FWHM 4.5 mm inter-update, and includes attenuation and scatter corrections. Fig. 3 is the PET/CT image of the patient.

We consider the undesired contact situation to happen quickly (in only one minute), thus the activity distribution in the patient’s body is presumably unaltered due to biological processes. (For that reason, in this study, dynamic PET images are not used to calculate the cumulative activity). We calculate the equivalent dose in a minute that the eyes of the AM phantom receive at the distances of 10, 20 and 30 cm in the two cases, standing opposite and side by side. The radiation weighting factors from ICRP Publication 103 are used for the dose calculation. Then, the doses from a source of $^{18}$F-FDG (1 MBq) for Opposite phantoms are then compared with those from point and tube source calculated by Sumi Yokoyama et al at the same distances.

This job can be done easily by just giving the two CT phantom file locations and setting the distance between them. All equivalent doses are computed by GAMOS software with the numbers of events chosen with a view to keeping the relative error below 3%. The physics selected is one of the physics lists of GAMOS, GmEMExtendedPhysics. This physics list selects the GEANT4 Livermore electromagnetic physics models and includes the radioactive decay of isotopes. The threshold for production of electron by ionization and gammas by bremsstrahlung is 0.1 mm, well below the size of the phantom voxels [15].

## 3. Results

The aforementioned calculations are accomplished without any shielding between the patient and the recipient, at the distance of 10,

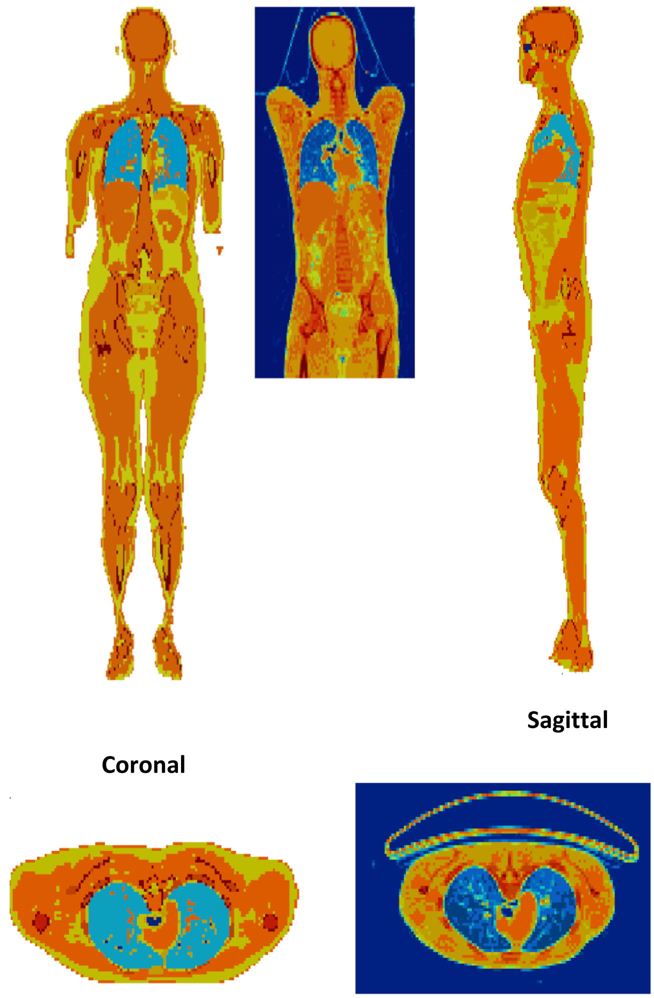


Fig. 2. The “Side by side phantom”.

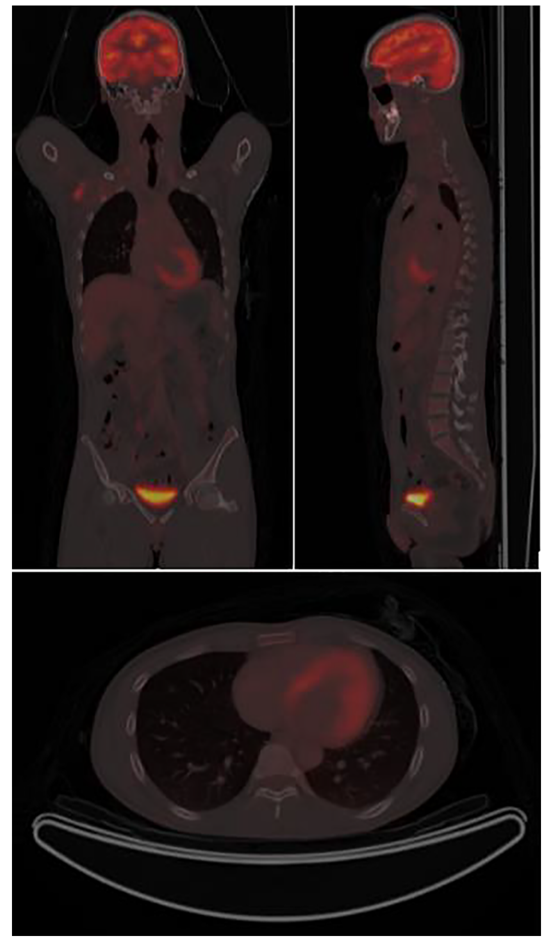

Fig. 3. The PET/CT image of the patient.

20 and 30 cm (Fig. 4). With stated distances: When two phantoms stand on opposite sides, equivalent doses from a source of $^{18}$F-FDG (185 MBq) to the eyes of AM phantom are 27.751, 11.120 and 2.781 μSv.min$^{-1}$ respectively; When the two phantoms lay or stand side by side, the corresponding doses are 15.170, 6.585 and 0.155 μSv.min$^{-1}$ respectively.

Fig. 4. Equivalent dose for eyes from a source of F-18 (185 MBq) calculating for “Opposite” and “Side by side” phantom.

Fig. 5 shows the equivalent dose per minute from a source of 1 MBq to the eyes at a distance of 10, 20 and 30 cm, calculated for the “opposite case” in this study, compared with the corresponding dose from point and tube source, calculated by Sumi Yokoyama et al with their eye model.

According to this result, from a source of $^{18}$F-FDG (1 MBq), the doses that a person receive from a patient source in a minute are smaller than those from point and tube source placed in front of the eyes at any distance. At the distance of 10 cm, the doses from point and tube sources are higher than that of the Opposite phantom by 27% and 6%. At a distance of 30 cm, the doses from point and tube source are almost equal, but those from the patient is still smaller than these doses.

## 4. Discussion

At any distance, the doses calculated in the “opposite” position are always greater than those of the “side by side” case. At a 10-cm space apart, the dose obtained by two phantoms placed opposite to each other is nearly double that in the other circumstance. The greater the distances are, the smaller the doses in both cases and the differences between them. When the distance was increased from 10 cm to 20 cm, the dose of the opposite case decreased by 60%, the dose for the other case decreased by 56%. When the distance was increased to 30 cm, the dose of the opposite case decreased by 90% and the other case decreased by 99%.

The eyes doses in the “side by side” case are smaller than the corresponding doses of the opposite case. This does not mean that standing side by side always brings fewer risks than the other case, but it depends on the distance from the high concentration of radioactive activity regions to the contacting person. This research presents the two common contacting circumstances for two people when they are talking or sleeping together. In reality, the contacting circumstances can be very diverse, especially for patients who have polio. Physical contact in too close proximity or direct contact with the body of patients such as hugging, bathing, or in physiotherapy for them all increases the risks for the contact and requires a strict time limit of contact. It should also be noted that the deposited dose will increase if a person comes in contact with many patients at the same time.

The dose differences in this study is resulted from the geometry differences of the sources and the eye models. These results are not meant to emphasize that the doses from the patient is smaller than those from the others, but rather demonstrate the differences in geometry on both phantoms and the sources that can lead to an incorrect estimation of the dose that a person receives from a patient. To have a better estimation, real geometries of both two persons and activity distribution in the patient should be used instead of a simple model, which can be done now by MPT.

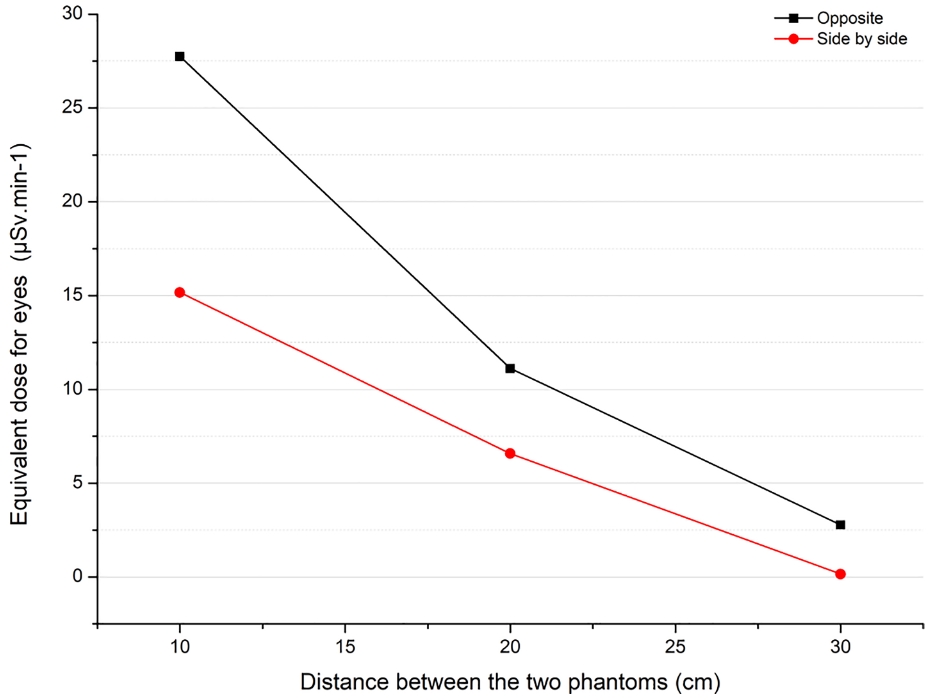


**Fig. 4.** Equivalent dose for eyes from a source of F-18 (185 MBq) calculating for "Opposite" and "Side by side" phantom.

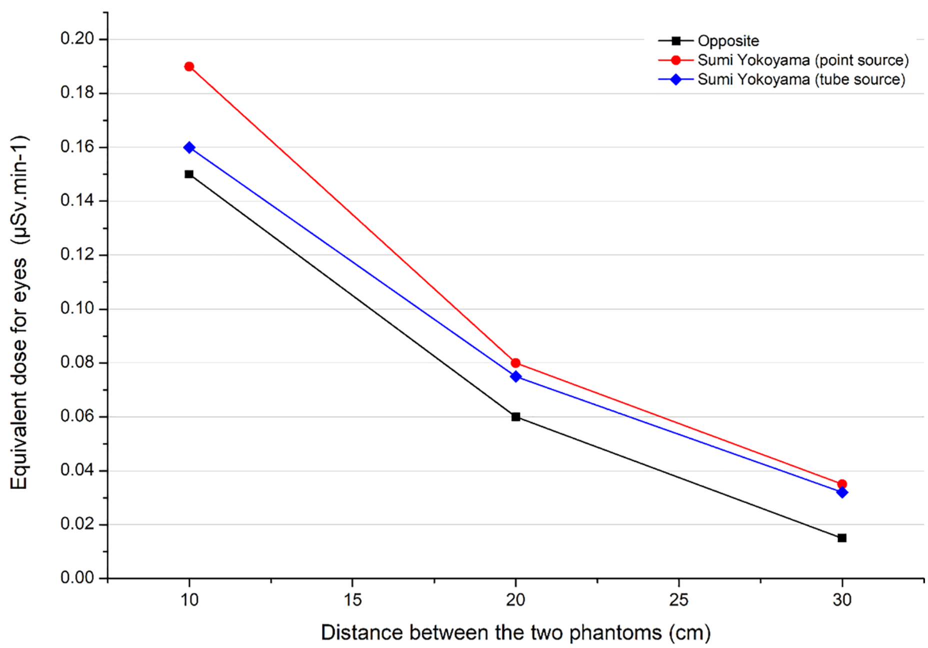


**Fig. 5.** Equivalent dose for eyes from a source of F-18 (1 MBq) for Opposite phantoms and corresponding dose calculated by Sumi Yokoyama et al.

In case a worker who handles radiopharmaceuticals comes in contact with a $^{18}$F-FDG point source spilled on a floor due to carelessness, or a staff comes in contact with the source trapped in an injection tube in a PET examination, the time of exposure is often small. In case a person comes in contact with a patient who needs special care or the person does not know about the condition of the patient, the long exposure time without shielding may occur. With the same activity and distance, although the dose absorbed from a patient is smaller than those in the two other cases, an extended exposure may aggravate the risks for the contact. To accurately estimate the cumulative dose that a person receives from a patient, the initial activity administrated to the patient, the distance, the duration of exposure and the transportation of radiopharmaceutical in the body of the patient have to all be included.

## 5. Conclusion

The calculations above serve the purpose of introducing a tool with the ability to merge two voxel phantoms, and input offered data through GAMOS (version 6.0.0) in order to estimate the doses to a person in contact with patients who have been treated with nuclear medicine. The equivalent dose for the eyes is chosen because the eyes is one of the organs that can be strongly influenced by radiation, causing cataracts [16]. Nonetheless, GAMOS can use the merged phantom to compute the deposited dose distribution in any organ. The results, when compared with calculations for point and tube sources of Sumi Yokoyama et al, also show that these model sources may overestimate the dose that a person receives from a patient.

The calculation is also carried out with the aim of radiation protection. If an accurate calculating circumstance presents a small dose even when the patient is at closed quarters with other people without any restrictions, there will be no need for isolation and undue anxiety can be reduced. The patients can be taken care of better and limitations occasioned by separation will be curtailed.

MPT allows users to merge two voxel phantoms in whichever distance, when standing oppositely to each other and when lying or standing adjacently. Users have to keep the position of the phantom representing the patient unaltered and only adjust the coordinates of the other phantom since the PET image is unaffected by the phantom merging. However, in case of long contacting time with patients, the activity distribution within the body of a patient will be changed. To exactly identify the accumulate dose in each organ, there is a need of including the changes in activity distribution due to biological processes. Users can easily compute the deposited dose to people interacting with patients at any distance by MPT and GAMOS software for various cases: nurses, caregivers, partner, children, drivers, so on and so forth. We emphasize that the deposited dose calculation for people who are in contact with patient should be estimated as accurately as it can be, before a medical decision is taken, as this will help protect the medical staff, the family members and others; and make the patient as comfortable as possible.

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