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CONSTRUCTION TOOL AND SUITABILITY OF VOXEL PHANTOM FOR SKIN DOSIMETRY

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ABSTRACT

This paper describes a new software tool called "*SkinVop*" which was developed to enable accurate voxel phantom skin dosimetry. A voxel phantom is a model used to describe human anatomy in a realistic way in radiation transport codes. This model is a three-dimensional representation of the human body in the form of an array of identification numbers that are arranged in a 3D matrix. Each entry in this array represents a voxel (volume element) directly associated to the units of picture resolution (pixel) of medical images. Currently, these voxel phantoms, in association with the transport code MCNP (Monte Carlo N-Particle), have provided subsidies to the planning systems used on the hospital routine, once they afford accurate and personalized estimative of dose distribution. However, these assessments are limited to geometric representations of organs and tissues in the voxel phantom, which do not discriminates some thin body structure, such as the skin. In this context, to enable accurate dosimetric skin dose assessment by the MCNP code, it was developed this new software tool that discriminates this region with thickness and localization in the voxel phantoms similar to the real. This methodology consists in manipulating the skin volume elements by segmenting and subdividing them in different thicknesses. A graphical user interface was designed to fulfill display the modified voxel model. This methodology is extremely useful once the skin dose is inaccurately assessed of current hospital system planning, justified justly by its small thickness.

1. INTRODUCTION

Since the early seventies, numerical dosimetry has been widely used in medical physics, both in academic and medical centers, because of the quality and reliability in the estimates of the radiation effects on the human body.

The development of mathematical heterogeneous human phantoms was a major achievement, which allowed dose estimates in regions where the experimental dosimetry becomes an complex activity to be performed, i.e. internal organs, in which the doses cannot be measured directly in the human body. In these phantoms, the size and shape of the body and their

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organs are described by mathematical expressions representing combinations and intersections of surfaces, such as planes, circular and elliptical cylinders, spheres, cones, etc.

The first mathematical phantoms was development by Fischer e Snyder [1; 2], representing a male adult, which also contains ovaries and an uteros. The anatomical data are based on the model of Reference Man, ICRP (International Commission on Radiological Protection) publication no 23 [3], and since then it has been known as 'MIRD5' phantom (Medical Internal Radiation Dose Committee of Society of Nuclear Medicine, Pamphlet No. 5).

For over two decades, various anthropomorphic models derived from the MIRD-5 model, allowed important advances in the assessment dose in human organs. However, despite the great efforts of researchers to seek mathematical descriptions which would be more accurate of body structures, the proposed methodology was very limited and unrealistic.

The great development on the medical image area allowed the acquisition of high resolution images (Computed tomography – CT or Magnetic Resonance Imaging), which in turn enabled the creation of a new model that solved the early limitations, known as as voxel phantom.

These new models offered the great opportunity of constructing virtual human phantoms from real persons, which are representation by a three-dimensional matrix whose elements are small volumes called voxels. For each volume element a material composition is assigned, which in turn are associated with the intensities of the pixels of medical imaging (Hounsfield numbers or grey values).

This methodology was introduced independently by Gibbs *et al.* [4] and Willians *et al.* [5], with quick acceptance by the academic public. Currently, there are several established models in the literature, representing different human genders and ages, e.g.: ZUBAL *et al.* [6], NORMAN [7], VIPMAN [8], VOXELMAN [9], MAX [10], etc.

These models were developed and adapted to reference values, in which the voxel dimensions have been scaled to match the body height and weight of the Reference Man [3], resulting in resolutions of 3-4 mm. However, such resolution limits some thin body structure discrimination, such as the skin, with thickness of approximately 1.5 mm for men and 1.2 mm for women, according to published estimates in ICRP 89 [11].

Organs and tissues that are not properly discriminated in the voxel phantom cannot be dosimetry evaluated using this methodology. The skin is an example once it cannot be properly represented with a thickness similar to the real, and therefore it is not accurately assessed using standard voxel numerical dosimetry.

On the other hand, the skin dosimetry study is extremely important in all radiotherapy procedures, once the skin is a continuously exposed organ on most procedures, especially in cases at which it is the object of study, such as skin cancers.

To solve these intricacies it has emerged in recent years new versions of the voxel phantom with better resolutions. This approach more reliable discrimination of organs and tissues, in

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addition to the inclusion of structures not previously discriminated, such as MAX 06 [12], a new version of MAX [10], with voxels of 1.2 mm and representation of thin and irregular organs, nearest the reference values.

However, this increased resolution require a significant computer memory so that the voxel phantom might be processed and executed by radiation transport codes, such as MCNP (Monte Carlo N-Particle) radiation transport code.

In this sense, the use of these new voxel phantoms with better resolutions are currently unfeasible to perform skin dosimetry, once it is impossible to insert them on the codes. In this way, skin dosimetric assessments are restrict to the earlier version phantoms (3 - 4 mm resolution), which overestimate the absorbed dose to uses the voxel resolution to represent skin thickness.

In this context, a new software tool called 'SkinVop' (Skin in Voxel phantom) was developed, and has the propose of discriminating the skin in the voxel phantoms with thickness and localization similar to the real. The principle used is based on the segmentation and the subdivision of voxel in different thicknesses, leading to an accurate dosimetric skin dose assessment by the MCNP code.

2. SKINVOP

The software tool 'SkinVop' consists of a calculation routine that segments medical images and discriminate the skin. This routine is either applicable to a voxel phantom already modeled in the MCNP code, which does not adequately discriminate the region of skin, or to medical image (in DICOM, JPEG, Bitmap formats), forming personalized voxel phantoms.

This tool was developed in MATLAB® (Matrix Laboratory) [13], version R2009b, due to its high performance in numerical calculation. Its main objective is to discriminate the skin with thickness and location similar to the real, obtaining as the output file an input file for MCNP code.

The geometric description of a voxel phantom in MCNP code is particularly performed through the feature known as Repeated Structure, which stands out by allowing the modeling of complex structures, irregular in their share and heterogeneous in their composition up to three dimensions [14].

The principle used in this feature is based on the ability to define, by the intersection of plans, a unitary structure called CELL and repeat it many times, arranging it in a sequence and inserting it into the geometric volume to be simulated. This tool allows subsegmenting voxels, so that the voxels belonging to the skin can be divided into skin and adipose tissue.

Figure 1 presents a schematic illustration of the methodology proposed for discriminate the skin in voxel phantom. Hereafter are presented the possible input files (Figure 1-A and B), the format in which the discriminated segmentations and skin are performed (Figure 1-C), the

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output file (Figure 1-D) and finally the voxel phantom that discriminates the skin region similar to real (Figure 1E).

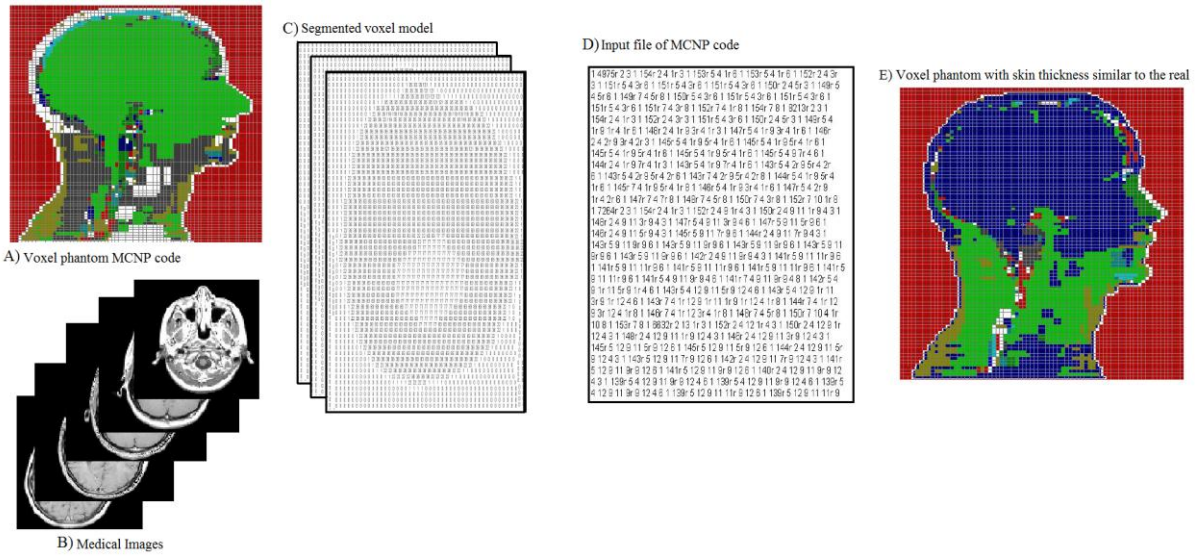

Figure 1. Schematic overview of the proposed methodology for adequately discriminates the skin in voxel phantom. A - B) Possible input files to the 'SkinVop'. C) Voxel model format in which the segmentation process and discrimination of the skin are performed. D) Output file of the 'SKinVop' and input file of MCNP code. E) Voxel phantom in MCNP code that discriminates skin with dimension similar to the real.

In the Figure 1 it is illustrated the main function of the software tool 'SkinVop'. However, this software is not limited to obtaining the input file for MCNP code. After the voxel phantom that discriminate the skin is modeled by the software, this phantom is inserted and executed by the MCNP code, which retrieve an output a file known as MCTAL. This file shows the absorbed dose in the voxels in a table format, in accordance with the initial conditions specified. However, MCTAL is usually of difficult access due to the amount of information it holds.

In this context, 'SkinVop' has a second assignment understanding the MCTAL, rebuilding the voxel phantoms into curves of absorbed dose, facilitating the evaluation of the results, presenting them graphically.

2.1. Working principle

The organs and tissues may be edited regarding the volume, shape and location within the body. The basic principle is called segmentation, which differentiates Hounsfield numbers or pixel grey values, subdividing the image into multiple regions that contain features in common with each other [15].

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Tissues having similar properties with respect to the imaging modality are represented in the diagnostic images by similar grey values (e.g., heart, muscle tissue). However, these values are similar but not equal, so that when segmented, they receive the same identification number (ID). The holder of the organ identification number is the voxel, enabling the modeling of voxel phantom.

The following will describe the segmentation techniques and the steps used by the software for the skin appropriate discrimination in the voxel phantom.

2.1.1. The graphical user interface

The purpose of the graphical interface is to facilitate the dosimetric evaluations by the MCNP code. This interface is a simple and direct form, in which the user enters his input file and processes the images to be run. Besides, the users can include specific information for modeling the voxel phantom, such as size, location, source, internal organs (lung, bones and soft tissue), among other information.

In Figure 2 illustrate the user interface. On the left, the user specifies the parameters and input file of interface, in the intermediate region are presented files used for modeling of the phantom. On the right are shown the MCNP input file that discriminate the skin and below it the absorbed dose profiles.

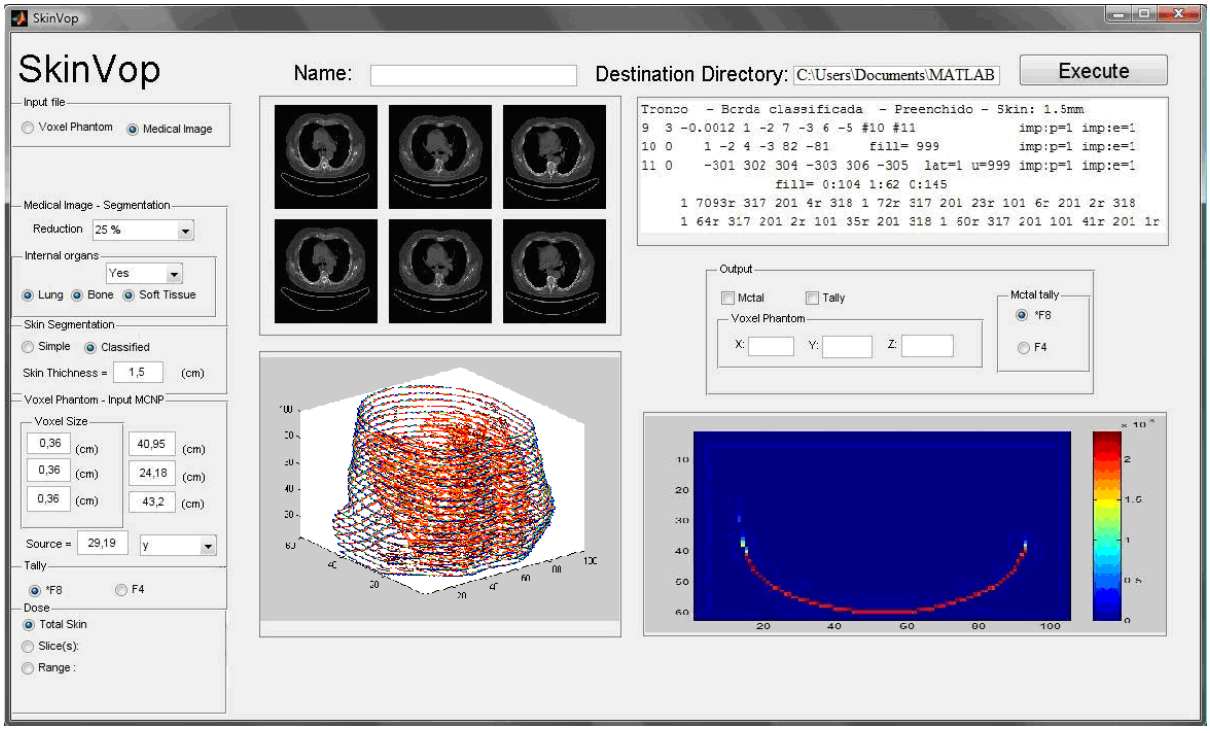

Figure 2. Graphical user interface illustration.

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2.1.2. Selection of the anatomical regions

The first manipulation technique is known as *Thresholding*, which assesses the pixel similarities and distinguishes and associates them to different regions, using a threshold *t* to classify which region the pixel belongs. For each threshold values n, n +1 regions are created [15].

Initially, the medical images are segmented using three threshold values (t_1, t_2 and t_3), which delimit the intervals of four distinct regions, assessing the grayscale: *ID=A* representing air, *ID=L* representing the lungs, *ID=T* for the internal tissues and *ID=B* for bones. These evaluations are represented by equations 1 to 4, respectively.

$$S(x,y) < t_1 \in A \Rightarrow Air \tag{1}$$

$$t_1 \leq S(x,y) < t_2 \in L \Rightarrow Lung \tag{2}$$

$$t_2 \leq S(x,y) < t_3 \in T \Rightarrow Tissue \tag{3}$$

$$S(x,y) \geq t_3 \in B \Rightarrow Bone \tag{4}$$

Where, $S(x, y)$ is the intensity of a pixel in the position (x, y). A CT image (Figure 3 A), submitted to the segmentation process proposed by the equations 1 to 4, results in the image of Figure 3B. In this new image, pixels that belong to the same region have equal *ID* values.

This thresholding technique may lead to erroneous segmentations in similar gray values, as is the case of regions representing the lungs and air. Another example is the noise of the image, such as the table used to accommodate patients during the image acquisition, are erroneously attributed to the bone region (Figure 3B).

In order to correct it was necessary to apply a new segmentation process known as *Growing region*. This technique uses the expansion of a region of interest, analyzing the similarity among the properties of neighboring pixels [15]. Initially, a central pixel $S(x_m,y_m)$ is discriminated the region of interest, which is expanded until there is a discontinuity between the intensities of neighboring pixels. This technique selects only the pixels that actually belong to the image, according to Figure 3C.

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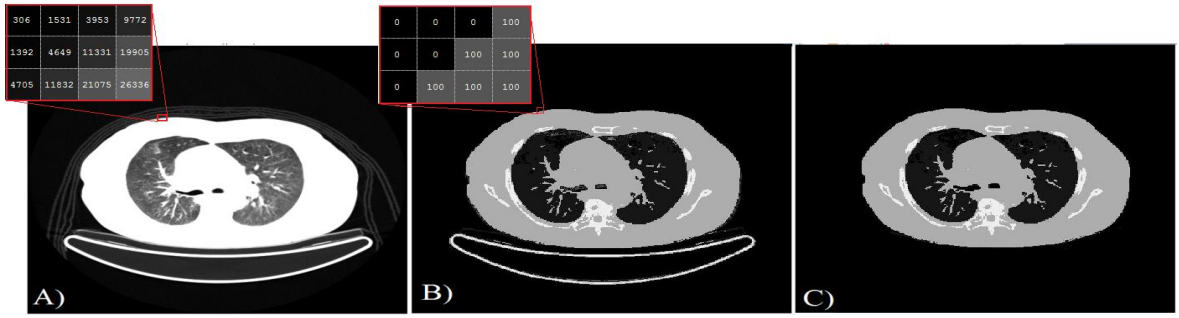

Figure 3. A) Tomographic image without segmentation. B) Segmented tomographic image represented by *ID*. C) Segmented tomographic image with interest region only, free of noises, such as the table.

2.1.3. Reducing image resolution

To model of voxel phantom that can be entered and executed in the MCNP code, it is necessary to reduce the resolution of the images.

The proposed reduction consists of two distinct stages. The first step optimizes the image area and restricts the spatial resolution only of the pixels of interest. This process is known as *Cropping* [15], in which are located limiters in the interest image, pixels related to minimum and maximum belonging to the image $S(x_{Mín},y)$, $S(x_{Máx},y)$, $S(x,y_{Mín})$ and $S(x,y_{Máx})$. All pixels outside the area defined by these limits are eliminated.

The second step consists in applying the interpolation techniques with the aid of the [*imresize*] function of the MATLAB® software. This function uses several methods, among which are: [*nearest neighbor*] that interpolates the pixels by their closest neighbors, removing them without loss of information of the gray levels, and [*bilinear*], which interpolates the pixels for adjacent average. The combination of these two methods allows the reduction of the image resolution without loss of important information by modeled phantoms.

2.1.4. Identification of the pixels representing the skin

At this stage, the images are binarized and homogenized so that it is possible to determine the pixels that belong to the skin.

The detection of the contour pixels is performed with the aid of the segmentation technique known as *Neighbourhood Pixel*. This technique analyzes all the possible connections of a neighboring pixel using the criteria chosen by the users and evaluating up to 8 pixels connections (four neighboring edges and four vertices) [15].

Initially, the edges connections of the pixels, known as N4 (S), were evaluated with the objective of selecting the pixels that belong to the region of the body contour (region C).

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Pixels belonging to the region of interest (region T) are attributed to region C in case one or more pixel boundaries border on the non interest region (region A), equation 5.

$$if((x+1,y)\vee(x-1,y)\vee(x,y+1)\vee(x,y-1))\in A\rightarrow(x,y)\in C \quad (5)$$

Where the symbol "$\vee$" means "OR." This assessment adds a new region in the image C (edge), represented only by a layer of pixels.

2.1.5. Classification of pixels representing the skin

The correct modeling of the skin with thickness and location similar to the real needs a more detailed level than the resolution allowed by the pixel size. So, the pixels previously designated for the body boundary region (region C), undergo a new process of segmentation, *Neighbourhood Pixel*, in which the connections of the pixel are evaluated the connections of the pixel, known as the edges and vertices that border the region A are determined.

In a pixel there are 14 possible different combinations of skin representation, which are designated by different *ID* used in the modeling of the voxel phantom in MCNP code. In equation 6 it is exemplified the evaluation of the N4(S)'s connections of a pixel that belongs to the region C. This pixel is associated with a specified *ID*.

$$if(\{[(x-1,y)\wedge(x,y+1)]\in A\}\wedge\{[(x+1,y)\wedge(x,y-1)]\in B\})\rightarrow ID(x,y)=21 \quad (6)$$

Where "$\wedge$" means "AND". If the left and upper neighbours belong to the region B and the right and lower neighbours belong to region A, the *ID=21* is designated to this pixel which specific *ID* for this connection.

Due to this segmentation, the selected pixels represent in the voxel phantom two distinct regions, adipose tissue and skin (the first 1.5 mm layer of the pixel).

All manipulations presented so far in this article have been described for pixels (two dimension), but a voxel phantom is a 3D figure and therefore one more dimension shall be used, significantly increasing the number of possible connections and locations of the skin representation in one voxel.

As one evaluates the pixel N4(S)'s connections, there are 14 different combinations of pixel skin representation, while the evaluation of the N8(S)'s connections it is possible to represent the skin in the voxel by 254 different combinations. However, only 24 of them have any significance to be disclosed in the software, disregarding 230 combinations with little or no probability of occurrence.

After the skin voxel classification, the software converts the array into MCNP code input file format, using the Repeated Structure tool.

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3. RESULTS

The software tool 'SkinVop' was developed in order to allow the construction of a voxel phantom by the use of medical images, as well as the reconstruction of phantoms already modeled in MCNP code, which must be written in the Repeated Structure form.

The program offers a graphical interface at which the users determine the possible input file and after the execution obtain an output file that is an input to the MCNP code, which discriminates the skin similar to the real.

This interface is a powerful tool for dissemination and use of software by different users. However, the current state of this work, is needed addition some tweaking the interface so that it can manipulate a significant amount of simultaneous information (medical imaging of the whole body).

It is believed that these intricacies can be solved by adjusting the proposed discrimination algorithm in different functions in the MATLAB software, i.e., the partition of the proposed methodology into steps, so to allow a fractionated processing.

The following examples consist in partial representations of the human body. In subsection 3.1 only the head and neck region of the phantom was rebuilt, while in subsection 3.2, it is built mainly the thoracic region of the phantom, with the partial addition of the head and lower limbs.

3.1. Reconstruction

The reconstruction of the voxel phantom for 'SkinVop' is feasible for all voxel phantom of the MCNP code, that do not discriminate the skin and if it does, it is in the wrong way.

In order to properly discriminate the skin region, the voxel phantom is initially subjected to a pre-processing that aims their conversion to matrix format, from which all skin segmentation procedure is performed.

In order to illustrate this reconstruction it was used the head and neck region of the voxel phantom known as MAX [10], consists of 90 slices, each one with 11,691 voxels of 3.6 x 3.6 x 3.6 mm^3 (Figure 4A). The skin in this phantom is initially represented by the first voxels of the body surface. However, throughout its extension are found some fake skin voxels, located beyond the body contour, an effect observed in the Figure 4A. This phantom was subjected to the 'SkinVop', allowing its reconstruction in two new models, Figure 4B-C.

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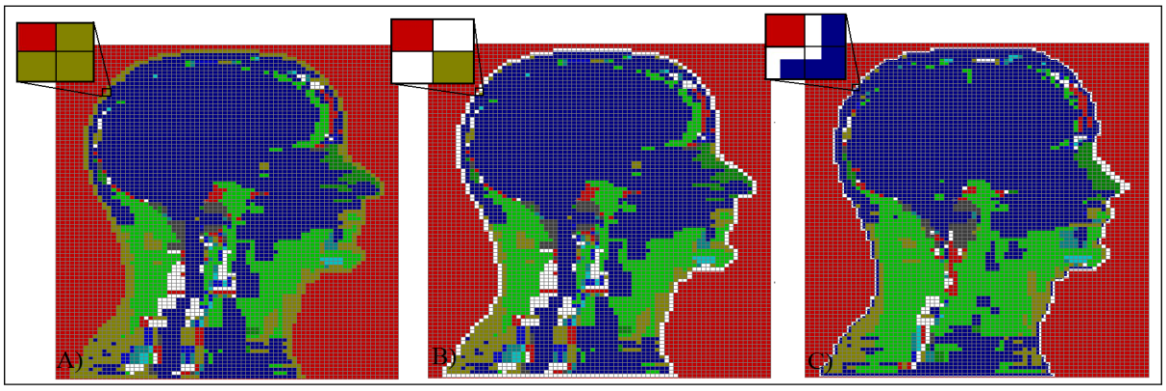

Figure 4. A) Region of the head and neck of the MAX (Male Adult Voxel Phantom). B) MAX reconstructed with skin thickness of 0.36 cm. C) MAX reconstructed with skin thickness of 0.15 cm.

The first reconstructed model eliminates the false skin voxels (located in the internal regions) present in the phantom, so that the representation of the skin is restricted to voxels bordering the region of the air (body contour). In this model, the skin thickness is not modified, once the skin is still represented by the entire volume of the voxel, as shown highlighted in Figure 4B. Throughout this study, it will be used the notation Simple Segmentation (SS) to depict this kind representation.

The second model proposed aims to match the skin thickness to the value specified by ICRP 89. In this context, the voxels previously discriminated as belonging to the skin are classified. This classification determines the skin possible locations on the voxel faces, subdividing it into two regions: skin (1.5 mm closer to the boundary with air) and adipose tissue (2.1 mm internal). Throughout the text, this representation of the skin will be expressed by the notation Classified Segmentation (CS).

The skin mass in the head and neck region of the MAX is estimated to be 827.9 g. This same region, when rebuilt by the SS model, is estimated to be 833.9 g, corresponding to an increase of 0.72% compared to the original estimated value of MAX. This increase is due to the inclusion of new skin voxels in interface regions between a slice and another. So, this new model discriminates correctly the skin around anatomical contours.

In the SC model, with the voxels subdivided in skin and adipose tissue, the skin mass is reduced to 287.05g, which represents 65.3% over the original MAX. This model allows a more realistic representation according to the specifications of the ICRP 89.

Table 1 shows the skin masses of the head and neck region of proposed reconstruction models, as well as the estimated percent of the skin mass to each model built.

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Table 1. Estimate of the skin mass representation of the head and neck region.

	Skin mass *(g)*	$\left(\frac{M_{Recons.} - M_{MAX}}{M_{MAX}}\right)$ *(%)*
MAX	827.9	-
Simple Segmentation (SS)	833.9	+ 0.72
Classified Segmentation (CS)	287.1	- 65.30

The evaluation of different proposed models for skin discrimination in relation to the representation of the original MAX (Table 1), presents an increase of skin mass in the SS model, which is justified in terms of discontinuous regions of the voxel phantom.

In this way, reconstruction based on the SS model designates the skin in all voxels belonging to the contour of the phantom, adding mass to the skin. However, the second CS model, with skin thickness of 1.5 mm, reduces significantly the mass and represents it more realistically.

3.2. Construction

The association of the medical image in 'SkinVop' allows the modeling of voxel phantom personalized that discriminate the skin region similar to the real, enabling an accurate dosimetric evaluation of a specific patient by the MCNP code.

The software works with medical images of different formats: DICOM, JPEG, PNG and BITMAP, which are automatically accessed to form a three-dimensional matrix.

In this study it was modeled the anthropomorphic phantom RANDO (*The Phantom Laboratory* - Salem, NY), commonly used in hospitals planning systems (Figure 5A). The CT images of the phantom were inserted in software, generating an input file of MCNP code.

Figure 5B-C shows coronal and sagittal image, respectively, of the built voxel phantom. This phantoms were segmented into four distinct regions, lung, skeleton, internal tissue (regions discriminated in the RANDO phantom), and skin (inserted by the algorithm with different thicknesses).

For this construction it was used 400 CT images, each with a resolution of 512 x 512 pixels. These images were reduced and interpolated by the software, resulting in matrix of 105 x 62 pixels, in order to build a voxel phantom that can be executed by the MCNP code, with voxels of approximately 3.9 mm.

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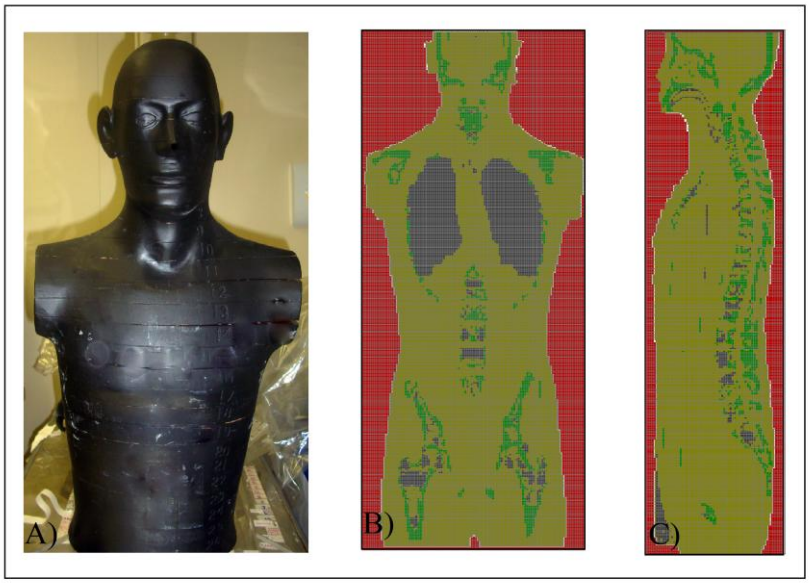

Figure 5. A) Antropormophic phantom known as RANDO. B) RANDO reconstructed by 'SkinVop', coronal sight. C) RANDO reconstructed by 'SkinVop', sagittal sight.

3.3. Absorbed dose profile in the skin.

After the voxel phantom is modeled and executed in the MCNP code, the result is output file known as MCTAL. This file is inserted in 'SkinVop', which organizes it in the proper body shape to facilitate data interpretation by the user, once the skin absorbed dose profiles are plotted graphically, according to Figure 6.

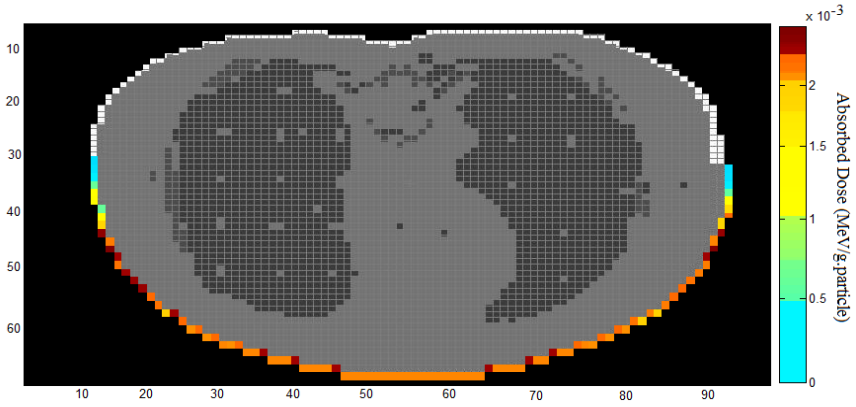

Figure 6. Skin absorbed dose profile in a slice of the voxel phantom of Figure 5.

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4. CONCLUSIONS

The current technological advances have made the numerical dosimetric a valuable tool for medicine, once it allows obtaining reliable and accurate dosimetric data, which in turn, result in more effective clinical procedures. This is due to the realistic voxel phantoms that enable dose estimate in the body regions at which the experimental dosimetry is an extremely complex activity to be performed.

The software 'SkinVop' is a comfortable and powerful tool for dosimetry, because it allows the achievement of accurate skin dosimetry by MCNP code. This is possible by enabling both the voxel phantoms already devoted in literature (that do not discriminated the skin or do it erroneously) and new personalized phantoms modeled based on medical images.

The new software tool is not only capable of adjusting skin voxel models to reference organ masses, but also to assist the user in the reconstruction of the absorbed dose curves by presenting it graphically and easily evaluating the results. However, it still needs some tweaking to be able to manipulate a significant number of medical images simultaneously.

This software is being validated through preliminary experimental measurements. So far the experimental data obtained are in agreement with the simulated data. However, a greater number is necessary of experiments validation to be completed.

The whole methodology is extremely useful once the skin is an interest organ for both radioprotection and radiotherapy areas, and with greater emphasis due to the imprecision of current hospital planning system in the evaluation of the skin dose, justified precisely by its small thickness.

Besides permitting the skin discrimination, this study developed an important methodology that suits the voxel phantoms to the imposed limitations by MCNP code, so that the obtained results are reliable and processed in reasonable computational time. The processing time is a limiting factor of the insertion of MCNP code in hospital dosimetry.

Nowadays, the insertion of the methodology in the hospitals is still not viable in terms of computational time. Though, it is worth as subsidy for accurate average estimates for all treatments, being the developed methodology of great importance for an assessment on the whole skin.

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