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3D modeling of bolus for producing by prototyping and use in radiation therapy

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ABSTRACT

Due to its vast number of occurrences, cancer has caused an economic impact on the public and supplementary health care sectors. It is estimated that more than 50% of patients diagnosed with malignant neoplasms need radiotherapy at some stage of their treatment, most of them treated with photon and/or electron beams. Due to the build-up effect (increase in dose in the matter from deposition on the surface to a point of maximum dose) caused by the interaction of photon beams with the irradiated tissue, bolus is often used in routine radiotherapy sectors to superficialize the point of maximum dose in the treatment region. The human body has complex surfaces that are often treatment regions in radiotherapy, but commercial bolus with a standard shape and length do not adapt perfectly to these surfaces. When this happens, air gaps may appear in the region, causing differences between the dose defined in radiotherapy planning and the dose delivered during treatment. In order to eliminate these air gaps and possible dose distribution errors, two methodologies for individualized bolus construction were proposed. In both cases, computed tomography images of the Alderson Rando male anthropomorphic phantom were used as a reference of the anatomy of a human body. From these images, one bolus model was constructed in the 3D modeling software 3ds Max by creating a polygonal mesh, while the other bolus model was constructed in the image computing software 3D Slicer, using segmentation tools. The software Creality Slicer 1.2.3. prepared the files for 3D printing. The prints of the files were made on polylactic acid filament on the Tevo Tarantula Pro printer. The bolus construction methodology using the software 3ds Max showed better results, as a greater contact area between the bolus and the phantom was observed when testing the fit of the printed bolus to the physical phantom. The 3D files of the virtual bolus will be available for future computer simulations. The printed bolus could be used in dosimetry with linear accelerators.

Keywords: **dose distribution, 3d printing, 3d modeling, teletherapy.**

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1. INTRODUCTION

According to the International Agency for Research on Cancer (IARC)[1], it is estimated that globally, 1 in 5 people develop cancer during their lifetime, with a mortality rate from the disease of 1 in 8 men and 1 in 11 women [1]. The adoption of factors associated with its development has increased its incidence rate over the last few years in Brazil. This can be verified by the projection indices regularly published in reports by the National Cancer Institute (INCA)[2]. INCA projects for the period 2023-2025, 704 thousand new cases of cancer in the Brazilian population, for each year [2].

Among the modalities available for the treatment of this pathological condition, radiotherapy (RT) is used in about 50% of new cases of diagnosed malignant tumors [3]. The technique consists of irradiating cancer cells using radiation sources close (brachytherapy) or distant (teletherapy/external radiotherapy) from the target to be treated [4]. The radiation allows to destroy the tumor or inhibit its growth. Therefore, a radiotherapy planning (RP) is carried out by a multidisciplinary team to define the most appropriate way to irradiate the patient [5].

Photons, electrons, protons, and heavy ions are used in RT. However, in Brazil, this procedure is often performed using photons and electrons [6]. The linear accelerator (Linac) used in teletherapy is characterized as the most used source of radiation [5]. The beams produced by Linac have the important characteristic that the maximum dose released in the irradiated tissue is located at a distance from the patient's surface. This distance increases according to the energy used in the treatment [7]. Some treatments in teletherapy, such as skin cancer and irradiation of the thoracic region of post-mastectomy patients, require superficializing of the point where the maximum dose deposition occurs, either to maximize the dose in the tumor, limit the penetration of the beam, preserving the surrounding structures, or even improving the uniformity of the dose in the tumor region [8].

A material equivalent to human tissue called bolus is used to conduct the maximum dose to the surface to be treated [8, 9,10]. There are a variety of bolus used in clinical practice. Many of these

[1] Intergovernmental agency that is part of the United Nations World Health Organization.
[2] Organ that assists the Ministry of Health in the development and coordination of actions for the prevention and control of cancer in Brazil.

are composed of materials such as paraffin, beeswax, acrylic polymer, Super Stuff[3] and Super Flab[4] [11]. One of the requirements for using the bolus is that it adheres well to the patient's skin, as the air layer between the bolus and the skin changes the dose determined in the PR unpredictably [12]. Considering that commercial bolus with a standard format do not always adapt perfectly to irregular surfaces such as the nose, ear and scalp, studies for the development of individualized bolus have been carried out popularized [9,10,13].

In search of bolus that best fit the surfaces of patients during radiotherapy treatment, several studies have shown the effectiveness of using individualized solid bolus produced by 3D printers in radiotherapy treatments [9,10,14,15,16]. The object is previously determined in a treatment planning system (TPS - Treatment Planning System), using medical images as a reference of the patient's anatomy, and then takes 3D shape on the print. However, there is still no established methodology for bolus modeling that is considered ideal, and there are many uncertainties and limitations in the use of existing ones [8].

Aiming to remedy the presence of air gaps between the bolus and the patient's surface, this work proposed the construction of individualized bolus produced by 3D printing using different methodologies. A methodology was associated with the creation of a polygonal mesh (PM) in the 3D modeling software 3ds Max. The other is based on image computing digital segmentation[5] tools using 3D Slicer software [17]. A color pixel count test on a sheet of ink positioned between the bolus and the surface of the phantom allowed defining the modeling with 3ds Max more efficiently.

2. METHODOLOGY AND RESULTS

The methodology of this work consisted in the computational modeling of bolus to be used in RT with Linacs. Two 3D bolus construction methods were proposed. The first made use of the 3D modeling software, 3ds Max. The second in turn made use of the 3D Slicer software. In the computational phase of this work, a notebook with the following specifications was used: Intel(R)

[3] Hydrophilic organic polymer, available in powder form. When prepared, it takes on a gelatinous form.
[4] Bolus based on latex-free vinyl. Available in sheets.
[5] Separation of regions based on similarity or discontinuity.

Core (TM) i5-7200U processor, 2.71 GHz CPU, Windows 10 64-bit operating system and 8 GB of RAM. On it were included Microsoft Office 2007 package (data organization), Autodesk 3ds Max 2021 Portuguese free version for student, teachers, institutions, and software evaluation (bolus modeling), 3D Slicer version 4.11 (image segmentation and bolus modeling) and Creality Slicer version 1.2.3 (study and preparation of files for printing). In bolus modeling, it was necessary to use CT images of the physical phantom Alderson Rando[6] [18] of the Dosimetry Laboratory of the Northeast Regional Center for Nuclear Sciences (CRCN – NE). To print the bolus models, the Tevo Tarantula Pro printer from the Simulation and Digital Fabrication Laboratory (SIMUFAB) of the Pernambuco Institute of Education, Science and Technology (IFPE), Recife Campus, and PLA filament in the natural transparent color were used. To evaluate the printed objects, an analog caliper to check the dimensions was used. In addition, white glue, gouache paint, bond paper, Digital Image Processing (DIP) and AnalyzerPixelRGB in house software were used to evaluate the internal fit of the bolus in the Alderson Phantom.

2.1. Definition of a human body simulator

In this work, the Alderson Phantom was used to represent the anatomy of a human body. Because this work demands the virtual representation of the head of a human body, a set of CT images of the head and neck region of the male Alderson Phantom was used. The images were obtained at the Clinical Hospital of the Federal University of Pernambuco (HC–UFPE) and were already in the possession of the Numerical Dosimetry Group (GDN) belonging to the IFPE. The set contains 475 slices, each 0.625 mm thick. The acquisition was performed on a GE PET-CT - 16 channels and adjusted to a potential of 120 kVp, electric current of 335 mA and a matrix of 512 x 512 pixels.

2.2. Getting virtual bolus

In both methods, the first step was a segmentation of the outer surface of the phantom. It was made in 3D Slicer software. Segmentation was performed using the segmentation editor module of

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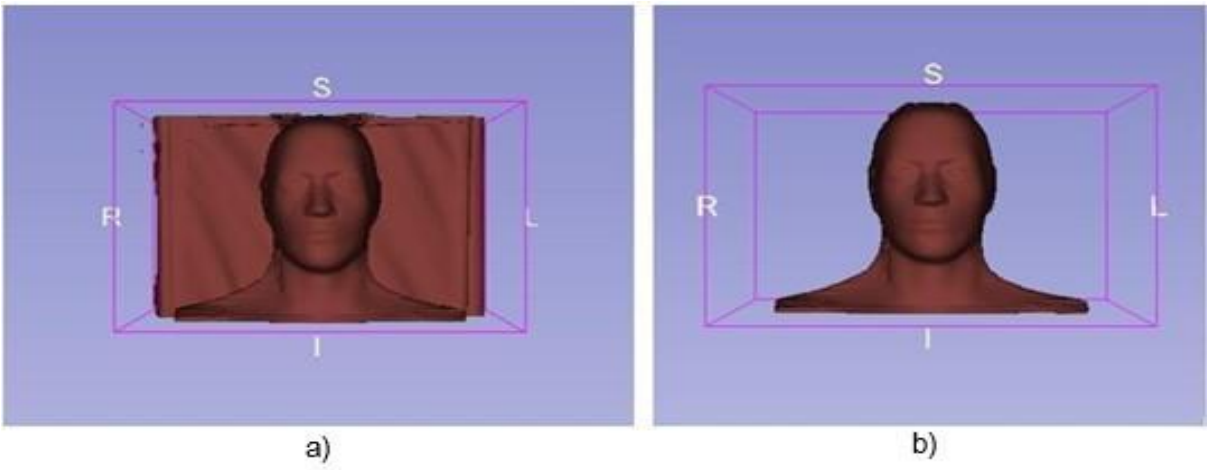
[6] Phantom representative of an adult male.

3D Slicer. Among the different options provided by the module, the Threshold tool proved to be the most suitable. This type of segmentation chosen takes into account the grayscale threshold to transform the input image into a binary image. The set of pixels is divided according to the gray level of the area that makes up the region of interest for the segmentation. In this work, to find and define the contemplation range of coverage of the entire external surface of the phantom, the values of the Hounsfield unit scale (HU) were considered as reference. Therefore, for the cited images, the applied ranges from -939.51 to -147.17, that is, in the range below the HU of water. With the segmentation performed, the smoothing factor 1 (maximum factor on 3D Slicer) was applied, so that the surface was as smooth as possible.

One of the problems encountered during segmentation consisted of the threshold covering the entire external surface of the phantom, but also including the surface of other structures (Figure 1). To resolve this problem, it was necessary to use the Erase and Scissors tools of the segmentation editor module. The Scissors tool was used in both limited and unlimited modes, aiming to preserve the structures of interest. Figure 1 shows the difference between the original segmented volume and the treated segmented volume.

Figure 1: *Segmentation of the outer surface of the virtual Alderson Phantom. a) Segmentation without treatment. b) Segmentation with treatment.*

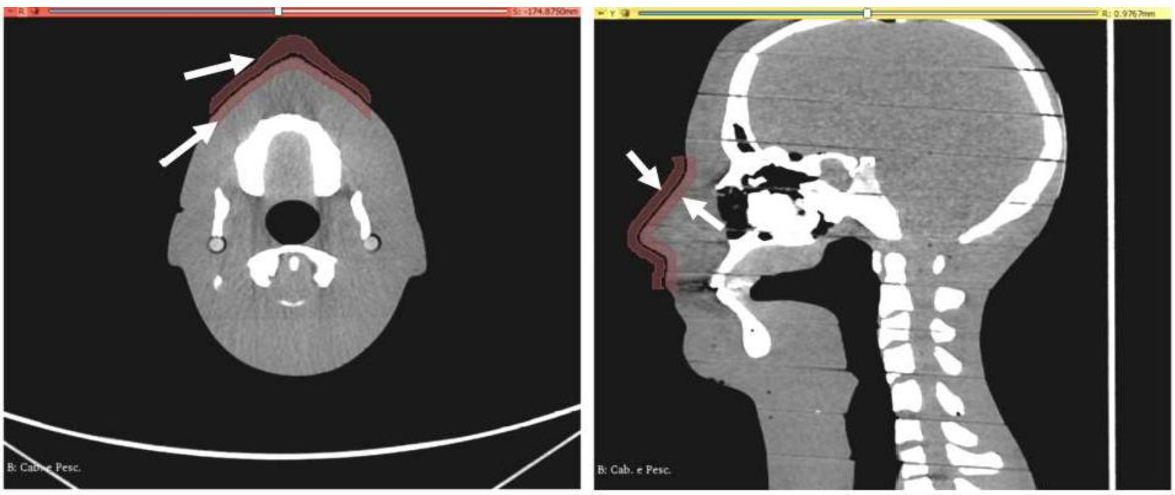


2.2.1 Getting the bolus in 3D Slicer

The modeling of the virtual bolus in 3D Slicer started with four main steps: determination of a reference volume representative of the phantom, creation of the volume corresponding to the bolus, determination of the thickness and extension of the geometry and generation of the STL file. The determination of the reference volume corresponds to Figure 1b.

Creating the bolus volume consisted of using the Hollow tool to create an outer shell of uniform thickness. When creating the shell (a copy of the phantom's nose skin), it was necessary to determine a thickness. In this work, the thickness of the shell corresponds to the thickness of the bolus, which was 5.0 mm. When creating the shell, two volumes started to occupy the 3D Slicer environment: the phantom and the shell that represents the bolus, separated by a surface. Once the thickness was determined, the delimitation of the bolus extension was carried out, having as a parameter the coverage of the entire nose, including margins for the irradiation field. For that, the Scissors tool of the segmentation editor module was used again, making a rectangular cut in which the nose region and margins for the irradiation fields were included. To finish this step, it was necessary to use the Islands tool, which, as the name implies, manages to separate a region from another region, so it is possible to separate the bolus from the rest of the phantom. The output file was saved in STL through the export files menu of the segmentation editor.

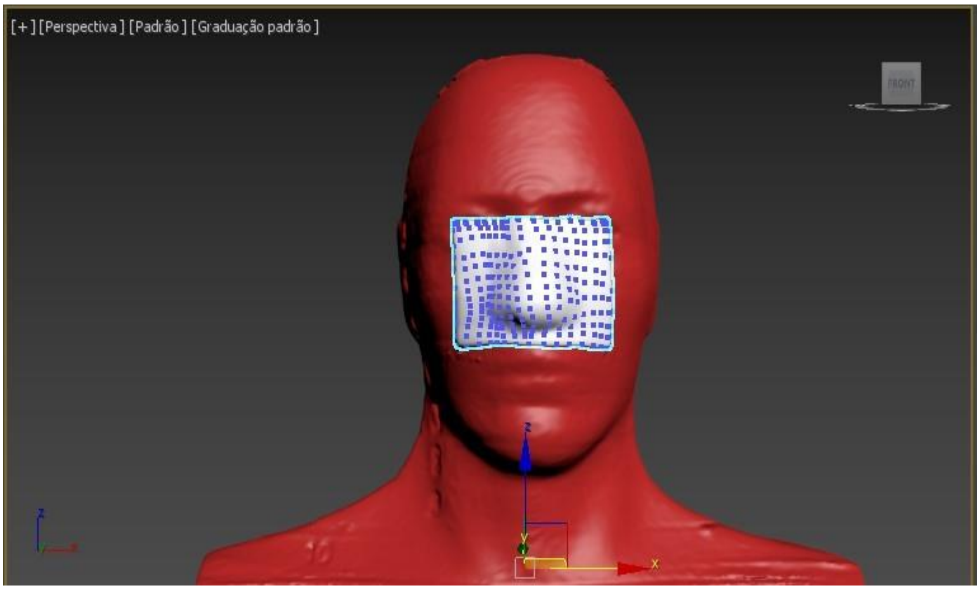
Figure 2: *Axial and sagittal views of segmentation volume and virtual bolus after exclusion of adjacent structures.*



2.2.2 Getting the bolus in 3ds Max

Obtaining the bolus in 3ds Max started from the previous segment of the Alderson Phantom surface. The modeling process chosen to build the virtual bolus was retopology. Retopology basically concerns overlaying a high-polygon (complex) mesh on a low-polygon mesh, while maintaining the anatomical information of the source mesh. In this work, the reference mesh is the external surface of the Alderson Phantom, which represents the skin of the Alderson Phantom. Already imported and loaded into 3ds Max, initially it was necessary to align the object's coordinates, transform the imported object into an editable polygon and select the object to draw on its surface, using the freeform menu. To start the drawing, it was necessary to establishment of 4 vertices in order to create a face. After creating the first face of four vertices, on the surface, the extend tool was used, which allows replicating the first face created, according to the direction intended by the user. The completion of the object took place by building face by face, performing welds when necessary, respecting the contours of the phantom. The absence of spaces between the reference object and the virtual bolus is necessary, so that when it is printed there are no air gaps between the physical bolus and the physical phantom (Figure 3). Once the modeling was finished, 5 mm of thickness was added in bolus and subsequently the 3D object was exported in STL format file.

Figure 3: *Using the shell and mesh smoothing tools.*



2.3 Bolus prototyping

The bolus impressions were performed by the printer Tevo Tarantula Pro of the SIMUFAB Laboratory at IFPE – Recife Campus. For printing, PLA filament (1.75 mm in diameter) in transparent natural color was used. The print files were prepared on *Creality Slicer* 1.2.3 software and the print settings used are shown in Table 1.

Table 1: *Print settings.*

Type of Material	**PLA**
Filament diameter	1.75 mm
Layer thickness	0.8 mm
Print speed	50 mm/s
Printing temperature	190 ºC
Fill	100%
Support type	*Raft*
Retraction speed	80 mm/s

After printing the bolus, the object was finalized by eliminating the support materials used in the printing. Printed bolus are shown in the Figures 4 and 5.

Figure 4: *External view of the 3ds Max bolus fitting in the physical Alderson Phantom. a) Anteroposterior view. b) View in profile. c) Super-inferior view. d) Infero-superior view.*

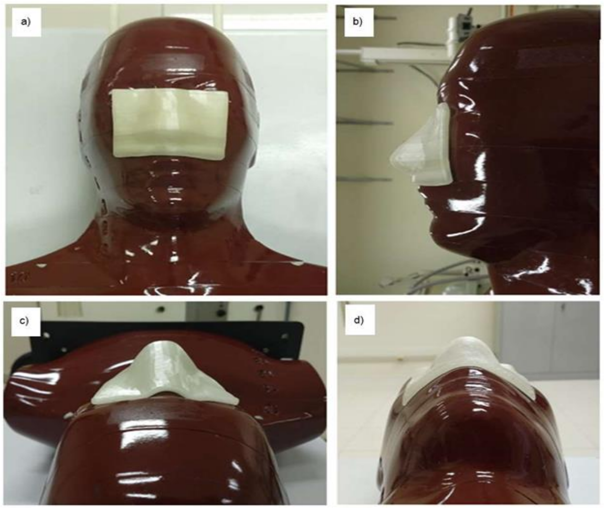
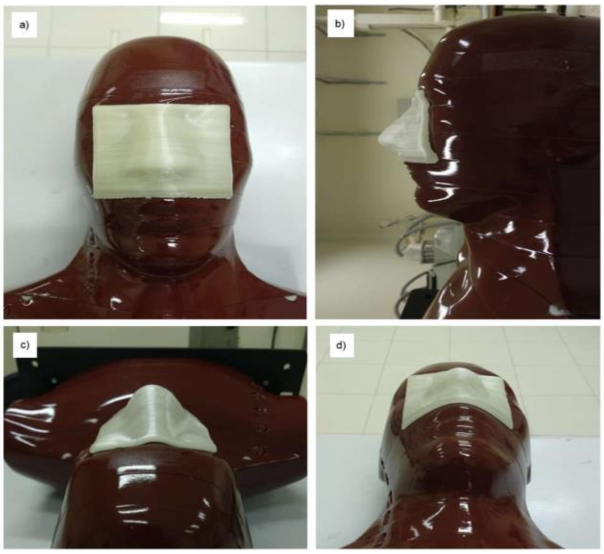


Figure 5: *External view of the Bolus 3D Slicer fitting into the physical AR phantom. a) Anteroposterior view. b) View in profile. c) Super-inferior view. d) Infero-superior view.*



Printing the 3ds Max bolus took 10.7h (20% faster) and required 44 g of PLA (14.72 m of filament). To print the bolus with 70 mm x 5 mm x 87 mm it took 13.2h and 54 g of PLA (18.20 m of filament).

2.4 Evaluation of bolus dimensions

The dimensions of virtual and physical bolus were obtained. The comparative result is presented in Table 2. A virtual measurement was performed on the STL files in the 3D Slicer using the Ruler tool to check the dimensions of the virtual bolus. The physical bolus were measured using a universal analog caliper (Make: Starrett, model: 125MEA, capacity: 150 mm, resolution: 0,02 mm).

Table 2: *Comparison result between virtual bolus and physical bolus.*

	3ds Max		***3D Slicer***	
Dimensions	**Virtual**	**Physical**	**Virtual**	**Physical**
Thickness (mm)	5	5	5 mm	4.9-5
Height (mm)	65	65	70	70
Width (mm)	82	82	87	87

These parameters indicate the security between the input data, which are virtual, with those obtained by the 3D printer. Because the bolus do not have the same width throughout the entire piece, the one with the highest value was considered. In the physical bolus obtained through the 3D Slicer, it was observed that the predominant thickness was 5 mm, however in the eye region, some areas had 4.9 mm. The thickness of the virtual bolus was uniformly applied, which indicates that this difference is linked to the printing accuracy of the 3D printer used in this work. A better assessment of uncertainty throughout the entire piece can be performed by obtaining CT images, since it is important that the thickness value determined in the radiotherapy planning is obeyed. Depending on the result, another printer or print setup should be studied and recommended for bolus printing.

2.5 Anatomical fit test and internal fit test

After printing the bolus, they were analyzed in two ways: the first verified whether the bolus fit the phantom (Figures 4 and 5). The second assessed the internal fit of the bolus in order to analyze the possible presence of spaces that could contain air. For the internal fitting test, A4 sheets of white bond paper, weight 75 g/m^2 were used. In addition to these, white glue suitable for use on paper and green gouache ink was used. A layer of glue was added over the paper and then a layer of ink was added, enough for both liquids not to run through the paper. The glue provided bonding to the mixture, while the paint provided color. The already prepared sheet was placed in the Alderson Phantom, in the nose region, with the surface with the ink facing upwards. Next, the printed bolus were inserted into the phantom. A sheet of paper was used for each bolus. A qualitative analysis was performed so that the more the internal surface of the bolus was marked in green, the more contact the surfaces would have had, consequently indicating the quality of the fitting of the parts. For the qualitative analysis, the DIP software and the AnalyzerPixelRGB software were used.

After the internal fitting test, photographs were obtained of the internal face of the bolus to verify the areas that came into in contact with the Alderson Phantom. These images were analyzed quantitatively using In house software developed by the Numerical Dosimetry Group belonging to the IFPE, available at: <http://dosimetrianumerica.org/producoes-cientificas/softwares/>. AnalyzerPixelRGB. The AnalyzerPixelRGB allows the segmentation of colored images and the quantification of colored pixels in the images.

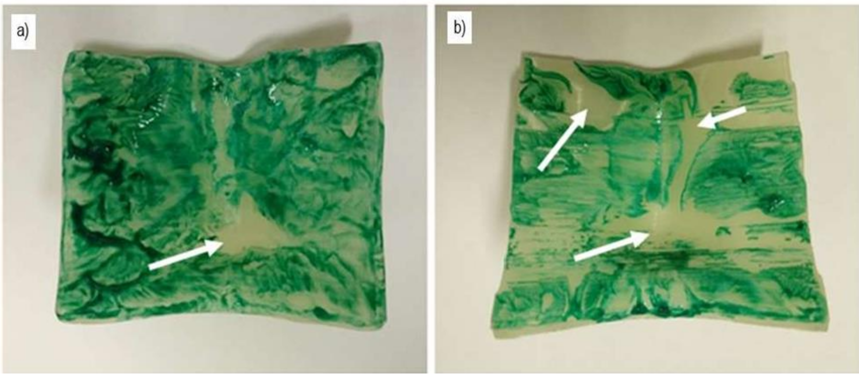
The images acquired (.jpg) in the internal fitting test have: the area that corresponds to the background of the images (environment in which the bolus were positioned for the photograph and which do not concern the bolus), the area of the bolus that came into contact with the phantom (green color) and the areas that did not have contact with the phantom (absence of the green color). To analyze the non-contact area, a sample of the same size and location of each image was taken (size: 489 x 287 pixels, location: x: 48, y: 73), by cutting the DIP, in order to exclude the background of these images. The first image was cropped using the cropping tool, in the option to select the area with the mouse. In order for the same dimension to be applied to the second image, the information from the first was used in the DIP, but this time, in the option to cut the area of an image by entering the location and dimensions.

With the G component image, it was possible to generate a TXT file, which lists the grayscale counts of the component. The TXT file contains three columns. The values in the first column correspond to shades of gray, the second corresponds to the pixel count for each shade, and the third corresponds to the relative count. Values from TXT files have been added to Excel spreadsheets. The first row of the columns was excluded (corresponding to tone 0), as well as the column corresponding to the relative count, and then the weighted sums were obtained for the values of each of the images. The ratio between the 3ds Max and 3D Slicer image values could show the difference between the amount of green areas present in the samples.

A segmentation was performed on the image samples using the PixelRGB Analyzer, for subsequent counting of green pixels. With the segmented images, the R, G and B components were separated using the “Save the R, G and B component images” tool of the PixelRBG Analyzer.

Figure 6 shows the markings on the inner surfaces of the bolus. The green marking indicates contact between the bond sheet (external surface of the Alderson Phantom) and the internal surface of the bolus. Some bolus areas, although small, did not show the green color, which implies that there was no contact with the external surface of the Alderson Phantom. These areas are indicated by white arrows in Figure 6.

Figure 6: *Internal fit test result. a) Bolus 3ds Max. b) Bolus 3D Slicer.*



The areas with no color indicated by the white arrows in Figure 6 were investigated by counting the pixels of the color images. In the qualitative analysis, the bolus produced in the 3ds Max software presented contact, in comparison with the bolus produced in the software a larger area of 3D Slicer. The weighted sum of the pixels corresponding to the green color in the 3ds Max bolus image was 8,273,826 pixels, while in the 3D Slicer it was 4,993,933 pixels. The ratio between the 3ds Max bolus and the 3D Slicer bolus is 1.6569 pixels, with the 3ds Max bolus image having a higher amount of pixels related to the green color. Analyzing only the numerical result, one of the software shows a significantly higher adjustment efficiency than the other. But it is necessary to analyze several other variables that can influence this internal fitting test and the user who is going to carry out this type of modeling, real ones are undesirable. need to be attentive because the presence of air in irradiation.

3. CONCLUSION

In this work, two methodologies were developed to obtain individualized virtual and physical 3D bolus, without the use of TPS during the process. In obtaining virtual bolus, the first methodology used the 3ds Max modeling software. The second used the 3D Slicer software with an emphasis on medical image segmentation tools. Both bolus were printed using a 3D printer.

The virtual and physical bolus, when compared, showed similarity in terms of dimensions, however, according to the data in Table 2, the 3ds Max is 0.3% better confident. Evaluating production speed, the methodology for obtaining the virtual bolus by the 3D Slicer presented more advantage. It was 18.7% faster. In 3ds Max, in addition to the time-consuming process of aligning the faces during mesh creation, there is the need for prior segmentation of the patient's skin in the medical images, in other software, in order to have the reference object. However, even though time is an important factor in radiotherapy treatments, the importance of eliminating spaces between the bolus and the patient's skin makes the bolus construction methodology by 3ds Max the most indicated in this work. In the verification test of the internal fit of the printed bolus, the one from 3ds Max indicated a larger contact area between the bolus – phantom (3dMax / 3DSlicer = 8.3 Mp/5.0Mp = 65% better). A better internal fit investigation can be performed by obtaining CT images.

Although the filament used in the printing was a transparent natural color, the printed bolus did not show transparency, but rather translucency, due to the thickness used in the object. To obtain transparency, other printers and materials can be studied.

The fitting test of the bolus in the phantom, as well as checking the dimensions of the objects, validated the methodology. Virtual bolus can be used to compose an MCE, while physical bolus can be used in dosimetry with the Alderson Phantom and a Linac. The implementation of a clinical routine can be studied in different environments and configurations (printing at the institution / outsourcing of printing.

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