Title:
Efficient Bolus Shaping for Cancer Care

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Introduction:
In the radiotherapy, a tissue-equivalent bolus material is used to conform closely to the target area of the patient skin in order to enhance the skin dose. The bolus should cover the skin perfectly [2,4]. However, for some irregular surfaces such as elbow, nose, and knee, airgaps may be generated between the bolus and patient skin. The airgaps lead to reduced dose delivered to the skin and consequently the treatment quality. The current method used in radiotherapy for cancer care is a manual process based on trial and error which is time-consuming and inaccurate. Usually, airgaps bigger than 5 mm will result in incomplete treatment. Although 3D printing methods have been introduced in bolus shaping with the improved accuracy, there is no daily clinical experience with the customized 3D printed bolus [3]. The time-consuming process and limited materials are main limitations of 3D printing techniques. In this paper, a process is developed to improve the accuracy of bolus shaping and fabrication efficiency using an unfolding-folding method which is one of the most prevalent techniques for the 3D object fabrication from planar sheets [11]. Using this method, a 3D model is first segmented, unfolded, and flattened into a set of 2D patches without overlapping. The flattened patches are then cut into the shape before folding back into the 3D shape. The formed 3D shape is compared with its original model to evaluate airgaps. As a 3D mesh model of the patient surface is usually complex with a large number of polygons, it is required to have some pre-processes such as mesh simplification to eliminate redundant information in the model and reduce the number of triangles and vertices of the mesh model for a trade-off between accuracy and efficiency.

The mesh simplification reduces the number of vertices, edges, and faces of a given mesh model while preserves details of the original model. For a shape unfolding method, criteria to measure the quality of flattened patches are: 1) a minimum number of patches generated without overlapping for a trade-off between the number of flattened elements and accuracy, 2) Smooth pattern boundaries for easy material cutting, and 3) the efficient process.

Main Idea:
Method: A process of the 3D bolus fabrication is developed with the minimum airgaps between the bolus and patient skin. A simplification process is first performed for 3D patient data obtained from 3D imaging techniques to remove redundant information. The simplified model is evaluated based on its reference model to ensure accuracy. The simplified model is then flattened into 2D patches in an unfolding process, followed by cutting and folding 2D patches into the 3D shape. The formed shape is measured by a 3D laser scanner to compare with its original model to evaluate the solution. The method flow is shown in Fig. 1. Details are as follows.

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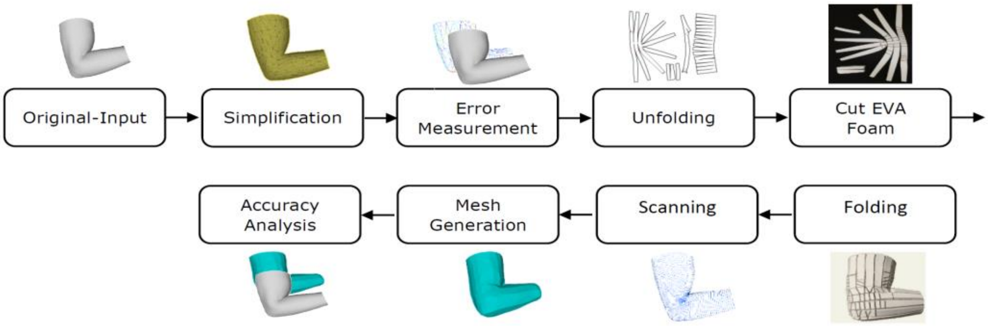


Fig. 1: Flowchart of the method.

Model simplification: A simplification process of the 3D mesh model is performed for the minimum information used in unfolding and folding processes. Three widely used simplification and remeshing techniques, Clustering Decimation, Quadric Edge Collapse Decimation [7], and Instant Field-Aligned [5, 6], are evaluated for a proper technique. The 3D mesh model is simplified in different reduction rates to analyze the difference between the simplified and original models. The outputs of the three techniques are then compared in visual and computational aspects. For the computation comparison, Hausdorff Distance (HD) is measured to compare the simplified and original models. The HD between two point-sets, M_1 and M_2, is defined as follows.

$$d_h(M_1, M_2) = \max_{a \in M_1} \min_{b \in M_2} \left\| a - b \right\| \tag{1}$$

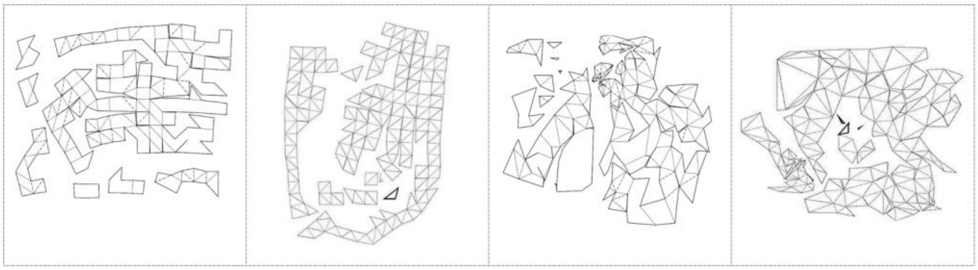
Since the one-sided HD is non-symmetric, $d_H(M_1, M_2)$ is defined as the maximum HD of two sides of a surface as follows.

$$d_H(M_1, M_2) = \max\{d_h(M_1, M_2), d_h(M_2, M_1)\} \tag{2}$$

The maximum and Root Mean Square (RMS) distances are used to find the largest generated distance as well as overall distances from the original model. Results show that the execution time of Clustering Decimation and Instant Filed-Aligned techniques are less than that used by the Quadric Edge Collapse Decimation technique. For the mesh quality, details of the original model are better preserved in simplified models using Quadric Edge Collapse Decimation and Instant Filed-Aligned techniques. However, for high reduction rates, the model simplified by the Quadric Edge Collapse Decimation algorithm is destroyed while the mesh boundary is preserved. In summary, the Instant Filed-Aligned technique shows better results than the other two techniques in the less execution time and difference between simplified and original models.

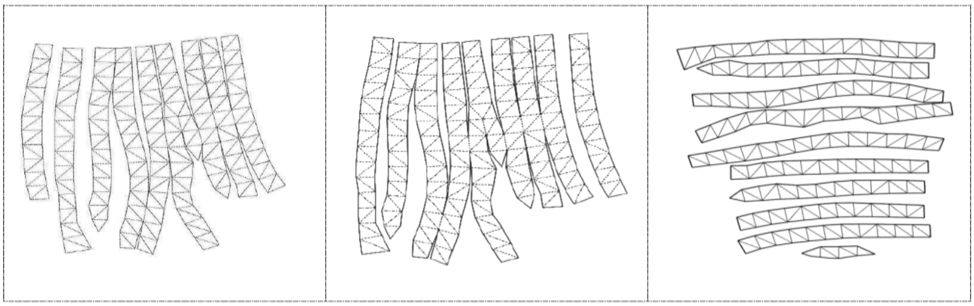
Model unfolding: The simplified model using a proper simplification technique is flattened into 2D patterns. Three common unfolding software tools, Pepakura Designer [8], SketchUp [10] and Blender [1] with different algorithms, are investigated to find the most appropriate one to meet the bolus forming requirement. The unfolding algorithm of the Blender tool uses edges with shorter lengths as well as steeper and concave angles for the high priority of cut lines. All faces are cut and then joined to create a bigger patch based on the edge preference. In the case of overlapping, the cutting operation is stopped and moves to the next edge. In Pepakura Designer, faces of the mesh model are connected or separated considering folding angles and areas of the face adjacent to edges, edges with sharper angles have preference to flatten. SketchUp uses a randomized algorithm without any creating distortion to flatten the resulting set of faces.

The unfolding process is performed in two ways, automatically and manually. Generated 2D patches from each tool are then compared in the number of patches and quality. Results show that simplified models using the Quadric Edge Collapse Decimation technique are unfolded into a large number of patches compared to the Instant Field-Aligned technique as shown Fig. 2. In addition, the generated patterns are complicated and irregular which makes the folding process challenging and time-consuming. The irregular patterns lead to a bunch of leftovers by cutting the bolus material. On the other hand, the simplified models using the Instant Field-Aligned technique are flattened into more order in triangle strips patterns. The manual unfolded patterns of a tumor model simplified by Instant-Field Align technique using the three unfolding tools are shown in Fig. 3.



(a) (b) (c) (d)

Fig. 2: Generated 2D patterns of the simplified tumor models using IFA and QECD. (a, c) patterns in Pepakura Designer, (b, d) patterns in Blender.



(a) (b) (c)

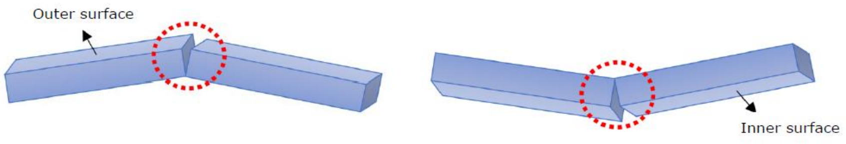
Fig. 3. The manual strip-based unfolding of the tumor model, (a) 2D patterns in Pepakura, (b) 2D patterns in Blender, (c) 2D patterns in SketchUp.

It is also found that SketchUp is unable to unfold the double-curved surfaces (not developable such as cylinders) automatically. Moreover, results show that manual unfolding process using SketchUp, besides the large number of patterns, unfolding is based on trial and error which is time-consuming. On the other hand, Pepakura Designer and Blender generate the same number of patterns. For functionalities, Pepakura Designer acts the best to edit and export 2D patches in various format files. The comparison of the unfolding tools is shown in Tab 1.

	Pepakura Designer	*Blender*	*SketchUp*
Automated unfolding procedure	✓	✓	×
Mountain and valley angles	✓	×	×
Export to .DXF format	✓	×	✓
Editable pattern	✓	×	×

Tab. 1: Comparison of unfolding software tools.

Evaluation: In the flattened patterns, two types of creases, mountain fold (convex) and valley fold (concave), are generated that should be assessed before cutting. Fig. 4 shows a mountain and valley folds created on the outer and inner surfaces of thick material, respectively.



(a) (b)

Fig. 4: The mountain and valley on thick material, (a) crease with a mountain fold, (b) crease with a valley fold.

Creation of the creases on thick materials is challenge in the folding process since the inner surface of a 3D model should remain smooth for a perfect fitting to the original surface as shown in Fig. 5.

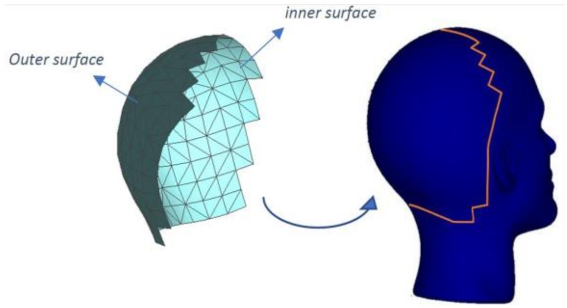
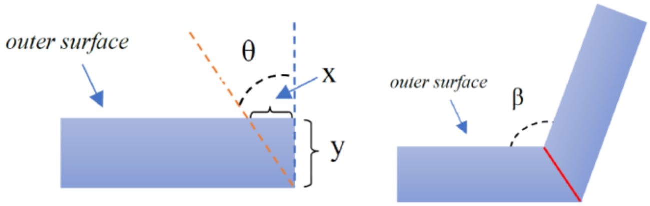


Fig. 5: Fitting a 3D model to the target surface.

Creases with the mountain fold can be created using a laser cutting machine as a semi-cut. As the laser cutting machine is unable to create an angle cut on the surface, creases with valley folds are deleted from exported 2D patterns for laser cutting and created manually. The creases with valley folds are then created for manipulation from the outside surface of the 3D model by making a V-shaped groove to keep the inner surface smooth as shown in Fig. 6. The mathematical formulation of finding a V-shaped groove angle is shown in Eqn.3 in which β is the valley angle, and θ is the angle of the V-shaped groove which should be cut from each edge.



(a) (b)

Fig. 6: The angle cutting (V-shaped groove) for creases with a valley fold, (a) cutting angle and corresponding cutting length, (b) Attaching of two edges for creation of crease with a valley fold after cutting.

$$\theta = 90 - \frac{\beta}{2} \tag{3}$$

$$\tan\theta = \frac{x}{y}, y = 10\ (mm), \qquad x = 10\tan\theta\ (mm) \tag{4}$$

Once unfolded patterns are cut into patches, they are folded back into the 3D shape. The pieces of the patches, the angle of the mountain crease is set using an angle finder, finally, the gap between two edges is filled using the glue. The total fabrication time is also measured as an important factor of this study. To evaluate the efficiency of the prototype fabrication, the processing time for each step, simplification, unfolding, cutting and folding, is measured separately. The accuracy of the formed prototype is evaluated by comparing it with its original 3D model. The prototype is first scanned using a ShapeGrabber 3D laser scanner available in the lab to form a surface model of the prototype. The scanner has accuracy up to 0.01 mm [9]. The accuracy is then evaluated for airgaps between the scanned prototype and its original model to meet the requirement. Fig. 7 shows the evaluation result of one of the case studies.

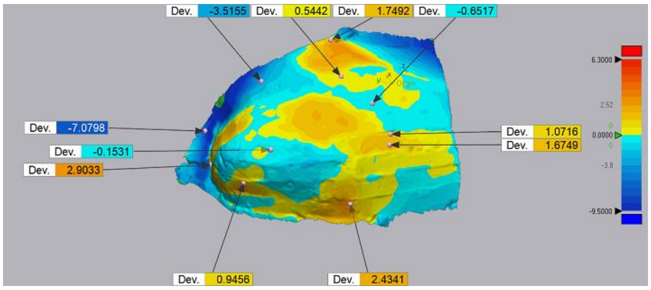


Fig. 7: Deviation of the tumor prototype with its original model.

Conclusion:

In this paper, an unfolding and folding process was developed for 3D bolus shaping with following solutions. 1) In the model simplification process, the Instant Field-Aligned technique generates simplified mesh models with more accurate and regular patterns. 2) In the unfolding process, Pepakura Designer acts as the best among investigated unfolding tools. On the other hand, unfolded patterns in SketchUp are generated based on trial and error in a large number of patches. 3) The instant Field-Aligned model is unfolded in a regular pattern based on triangle strips, which makes the folding process easier. 4) The average total fabrication time is around 2 hours, which is considerably less than time used by the 3D printing technique. 5) Results of the accuracy evaluation show that the deviation between the fabricated prototype and original model meets the objective of this study.

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