Distance-Aware Smoothing of Surface Meshes for Surgical Planning

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ABSTRACT

The evaluation of spatial relationships between anatomic structures is a major task in surgical planning. Surface models generated from medical image data (intensity, binary) are often used for visualization and 3D measurement of extents and distances between neighboring structures. In applications for intervention or radiation treatment planning, the surface models need to exhibit a natural look (referring to smoothness of the surface), but also to be accurate. Smoothing algorithms allow to reduce artifacts from mesh generation, but the result is always a tradeoff between smoothness and accuracy. Required features will be removed and distances between adjacent structures get changed. Thus, we present a modification to common mesh smoothing algorithms, which allows to generate smooth surfaces models while distances of neighboring structures are preserved. We compared our distance-aware approach to conventional uniform smoothing methods and evaluated the resulting surface models regarding smoothness and accuracy for their application within the context of surgical planning.

1. INTRODUCTION

The morphology of anatomic and pathologic structures and their spatial relations are examined for planning of surgical intervention or radiation treatment. Surface models of anatomical structures are derived from medical image data, e.g. from computed tomography (CT) or magnetic resonance imaging (MRI). Medical image data often suffers from a limited resolution and anisotropic voxels (slice thickness is considerably larger than the in-plane resolution). For generating surface meshes, the target structures need to be identified by user interaction, automatic or semi-automatic methods. Thus, the resulting 3D models may contain several artifacts, such as staircases, terraces, holes, and noise. For a correct perception of shapes and spatial relations, the models are required to look naturally to resemble e.g. the intraoperative experience of surgeons. The natural appearance refers to smoothness of the surface, since anatomical structures usually do not exhibit sharp edges. Potential artifacts can be reduced during mesh generation or by additional mesh postprocessing (smoothing). Unfortunately, this may alter the structures' volume, extent and relevant interstructure distances. The employment of accurate models (in terms of distance and volume preservation) is essential for surgical planning to ensure a correct computation and visualization of safety margins and potential infiltrations.

However, smoothing methods, in general, offer a tradeoff between surface smoothness and accuracy. Context information, such as critical neighboring structures are not considered. Thus, we suggest an extension to these common mesh smoothing approaches that takes local distances between relevant structures into account. The minimum interstructure distances will not be altered, whereas the structure gets smoothed according to the selected method and corresponding parameters. We refer to this concept as *distance-aware* smoothing. This modification is important in 3D diagnostic or surgical planning applications where potential infiltrations need to be assessed. Especially the neck is a good example where several critical structures (e.g. arteria carotis, vena jugularis, sternocleidomastoid muscle, lymph nodes, salivary glands) are located very close and the exact local distances are relevant for the planning of surgical interventions or further treatment. For planning of an intervention to remove a tumor or enlarged lymph node, which is directly adjacent to these structures, the distances need to be determined and visualized correctly. If mesh generation and smoothing would alter those distances, the intervention planning could lead to wrong conclusions. Thus, we applied our modified smoothing approach to sample data acquired for neck surgery planning and investigated the influence on

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smoothness, distance and volume preservation.

2. RELATED WORK

Medical surface models are generated from intensity data or binary masks, which are derived from volume data by preprocessing and segmenting the target structures (e.g. bones, vessels, liver, lymph nodes, ...). Especially in clinical routine, the image data are often composed of anisotropic voxels, which may introduce artifacts to the surface models (see Fig. 1). The data can be transformed into a surface mesh using e.g. the Marching Cubes (MC) algorithm [12], or level-set methods [21]. Several methods take care of artifacts during mesh generation, e.g. by additional trilinear interpolation and subdivision of the surface elements (Precise Marching Cubes [1]) or iterative constrained relaxation of the surface (e.g. Dual Marching Cubes [14], Constrained Elastic Surface Nets (CESN) [9, 6]).

Noise, staircase artifacts, or plateaus resulting from the limited resolution and slice thickness can also be reduced after mesh generation by appropriate smoothing operations (e.g. Laplace filter, Mean Curvature Flow [8]). These methods allow to smooth surface models but often cause volume shrinkage and loss of features. More specialized methods (Laplace+HC [20], Taubin's $\lambda|\mu$ smoothing [19]) try to prevent from shrinking volumes by an additional correction step moving the vertices back toward their original position. For models containing extreme staircase artifacts (refer to the tumor model in Fig. 1 for an example), an appropriate parameter configuration is nearly impossible, if a natural appearance and accuracy are required simultaneously.

Several approaches are designed to reduce noise which has been introduced e.g. during laser scanning [8, 20, 18] or has been added to a perfect artificial reference model [5]. However, these methods focus on the preservation of sharp edges in non-medical data. Their direct application to medical surface models may give unsatisfying results, since anatomical structures typically have smoother shapes and the staircase artifacts would be interpreted as feature edges and thus be preserved. Bade et al. [2] applied different mesh smoothing algorithms to surface models generated from binary image data and compared the results with respect to artifact reduction and volume preservation. They identified the Laplace+HC and Taubin's $\lambda|\mu$ smoothing as most appropriate for most anatomical structures with respect to volume and feature preservation. Additionally, they suggested a constraint for vertex placement during mesh filtering to preserve accuracy [3]. These smoothing algorithms are suitable for smoothing of small artifacts (staircases, noise) with simultaneous preservation of accuracy. Large terracing artifacts can still not be reduced sufficiently.

All of these widely used methods apply constant smoothing parameters to the target structure. In contrast, there are other methods available, that adjust smoothing according to classified features [11, 15], local mesh density [4], or even apply different filters [7].

However, all approaches focus on single structures without involving the relationship to neighboring structures. Within the context of medical visualization for intervention or treatment planning, these local dependencies between neighboring structures (e.g. a tumor, which is located close to critical structures, such as vessels or muscles) become important. They can be expressed by measuring the(minimum) Euclidean distance between the target structures [16]. Involving the knowledge on the local neighborhood during mesh smoothing may offer a way to generate surface models with reduced staircase artifacts on the one hand, while keeping accuracy in terms of distances to reference structures.

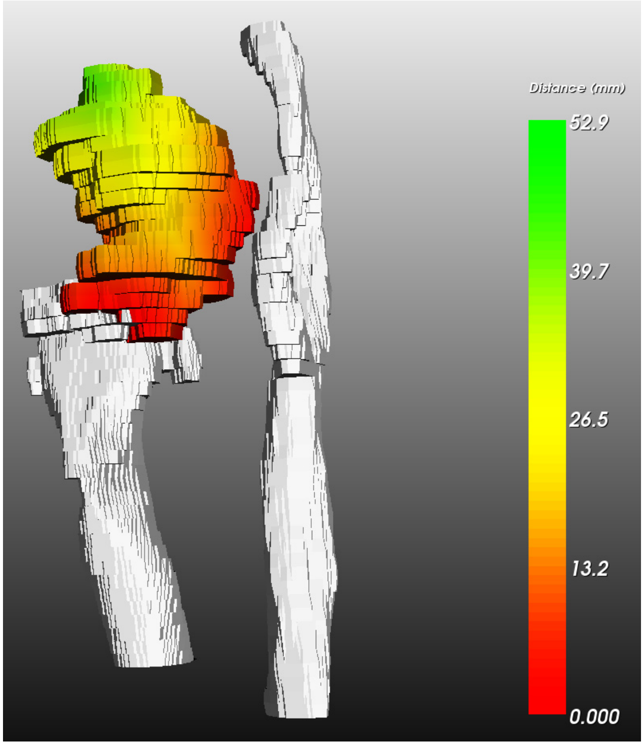


Figure 1: Three sample structures are shown which have been generated from binary masks using Marching Cubes algorithm without further pre-/postprocessing. Left: trachea, right: vena jugularis, middle: tumor (colored by Euclidean distance to the other structures, in mm).

3. METHODS AND DATA

To overcome the problem of altered inter-structure distances during mesh smoothing, we suggest an additional weighting parameter which is aware of the spatial context. For each vertex v_i of a given surface mesh (M_1), we compute the minimum Euclidean distance to the surface of a given reference mesh (M_2) according to Roessling et al. [17]. Subsequently, we scale the distance values (β_i) to the range of [0, 1], whereas the closest vertex of mesh M_1 to M_2 is assigned a 0 and the furthest vertex is rated with 1. For example, a simple Laplacian mesh smoothing filter with distance-aware weighting can be described by Eqn. 1, where the general weighting factor λ is replaced by λ', which is multiplied by the vertex specific weighting β_i.

$$v_i' = v_i + \frac{\lambda'}{m}\sum_{j=1}^{m}(u_j - v_i) \quad (1)$$

$$\text{with } \lambda' = \lambda \cdot \beta_i \quad (2)$$

$$v_i, u_j \in V, v_i \neq u_j, \forall u_j \in U^1_{v_i}, m = \left|U^1_{v_i}\right|$$

$$V \text{ - all vertices of } M_1$$

$$U_{v_i}^1 \text{ - 1st order neighbors of each vertex in } V$$

$$\beta_i \text{ - distance-related weighting factor for each vertex in } V$$

Similar to Eqn. 2, the vertex specific weighting can also be combined with any other smoothing method, irrespective if there is an additional back correction step involved (e.g. Laplace+HC, Taubin's $\lambda|\mu$). The weighting applies directly to the final displacement vector of each single vertex. As an alternative, a more specific weighting, which additionally depends on the position of the vertex in M_1 with minimum distance to M_2, might allow to focus certain features.

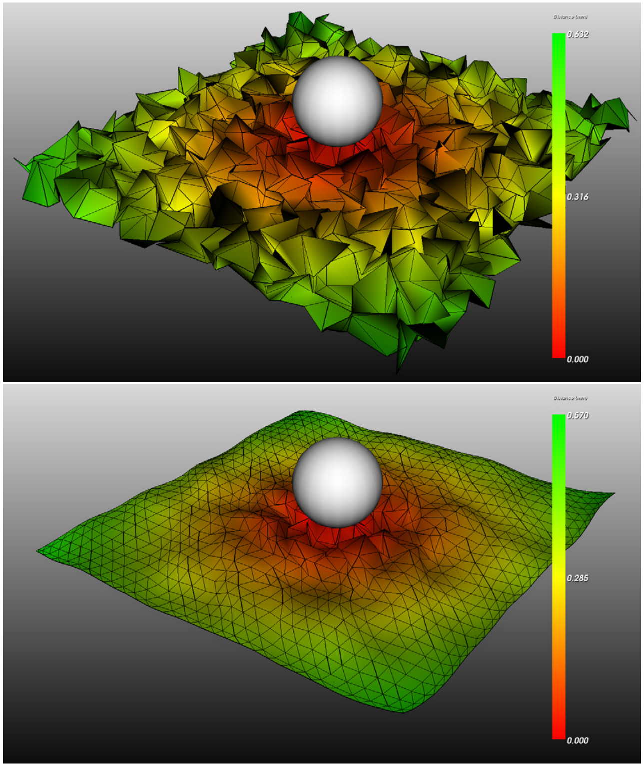


Figure 2: Artifical testing scenario. Top: The initial surface models. Bottom: Distance-aware Laplacian smoothing applied to the plane with linear scaling. The plane is colored by Euclidean distance to the sphere (in mm).

Inspired by our major application scenario (risk analysis around a tumor), we created an artificial dataset, which consists of a noisy plane with a sphere located close to it. Fig. 2) shows this testing scenario to describe the influence of locally adaptive mesh smoothing. By default, the scaled Euclidean distance can directly be used for vertex displacement weighting. This yields a linear increase of the default smoothing factor with increasing distance . However, modified scaling themes will give the opportunity to focus regions with higher or lower weighting and define "safe" regions which are not altered by mesh smoothing at all (see Fig. 3). In surgery, relevant safety margins are e.g. 2mm, 5mm, and 10mm. Thus, we defined a sample safety margin of 10mm, that completely preserves vertex positions (weighting equals zero). Vertices with higher distance values are linearly weighted accordingly. Additionally, we applied a sample non-linear scaling function (e.g. $\lambda' = \lambda \cdot e^{3\beta_i}$, which gives the opportunity to define regions with stronger or less smoothing without hard thresholds. Irrespective of the scaling theme, a continuous function needs to be guaranteed to avoid interfering visual artifacts.

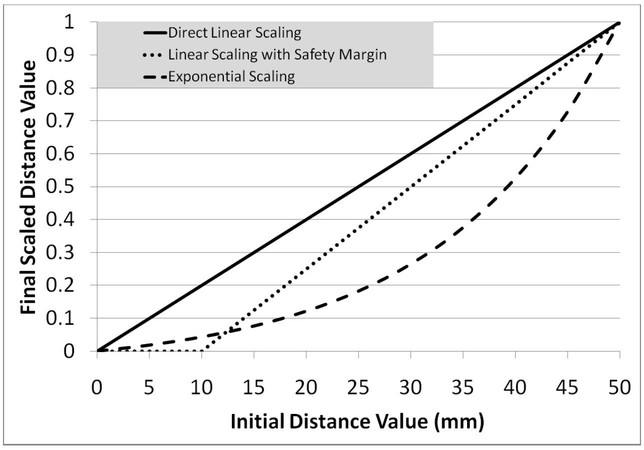


Figure 3: The applied sample scaling functions are shown. By default, direct linear scaling of the Euclidean distances is used. Additionally, a safety margin or an exponentional function might be appropriate.

To evaluate the described distance-aware smoothing, we employed a CT dataset (voxel size 0.453×0.453×3mm) of the neck and picked three close located structures for demonstration (see Fig. 1). Smoothing is applied to the models of the tumor and the vena jugularis. For the tumor model, the models of vena jugularis and the trachea serve as reference structures. For the vena jugularis, the tumor is used as reference model. For the latter, the trachea is ignored since it is to far away from the vessel to be relevant for special consideration. All structures have been segmented manually by medical experts, thus the surface models have been generated from the binary segmentation masks, which yields strong terracing artifacts. These artifacts could also be reduced by involving e.g. intensity data to model generation, but the problem of strong terracing artifacts still persists, since the usage of intensity data is not always feasible (e.g. due to image inhomogeneities) [13]. Thus, we generated surface models from the binary data via MC and subsequently applied different sample mesh smoothing methods: standard Laplacian smoothing, Laplace+HC, Laplace with node position constraint. For the latter, we defined cubical voxel cells with the original voxel dimensions for each vertex, whereas the displacement of the vertices during smoothing is restricted to these cells. Distance-aware smoothing has been combined with standard Laplacian smoothing to demonstrate its influence to distance preservation. We applied very strong smoothing to emphasize the differences between the results of the methods. For the tumor model, we used 30 iterations with λ=1 and for the vessel model, 20 iterations have been applied (for all involved methods). The additional parameters of the Laplace+HC filter have been

Table 1: Results of a comparison of the smoothed tumor models (with the mentioned methods) and the initial MC reference model of the same data. To emphasize the differences between the methods, we applied very strong smoothing with the following parameters (used for all related methods): 30 iterations, λ=1.

Smoothing method	Hausdorff distance to original model (mm)	min. Euclidean distance to vena jugularis (mm)	volume (%)	avg. normal curvature (degree)
Original	0	0.35	100	14.69
Laplace	3.06	2.17	88.91	4.02
Laplace with node position constraint	1.53	1.65	94.43	9.02
Laplace+HC	1.16	1.07	97.40	11.12
Distance-Aware Laplace	2.51	0.39	93.46	7.30
Distance-Aware Laplace (with 10mm safety margin)	2.41	0.35	95.34	9.96
Distance-Aware Laplace (with exponential scaling)	2.47	0.36	94.84	9.30

set to α=0 and β=0.5 according to Bade et al. [2].

The resulting surface models have been compared regarding smoothness, distance and volume preservation. For smoothness, we employed the normal curvature which we defined as the maximum angle between the vertex normal and the normals of all incident faces (similar to [10]). Volume preservation is used to demonstrate the global error introduced by each mesh smoothing method. Distance preservation is evaluated with two measures: the Hausdorff distance, which is determined between the smoothed and the initial surface (to show changes within the model) and the minimum Euclidean distance, which serves to show the relation between neighboring structures. It is obvious, that our presented smoothing modification can only focus on preservation of the inter-structure distances. The Hausdorff distance will definitely give results which are close to the values of standard Laplacian smoothing, since non-relevant parts of the model will receive only small modifications of the smoothing weighting.

4. RESULTS

The comparison of our proposed modification and standard smoothing methods showed, that it is possible to receive visually smooth surface models (even with strong terracing artifacts) while preserving relevant distances to neighboring structures. The application of distance-aware smoothing to two sample structures with different topological properties gave similar results.

4.1 Model of the Tumor

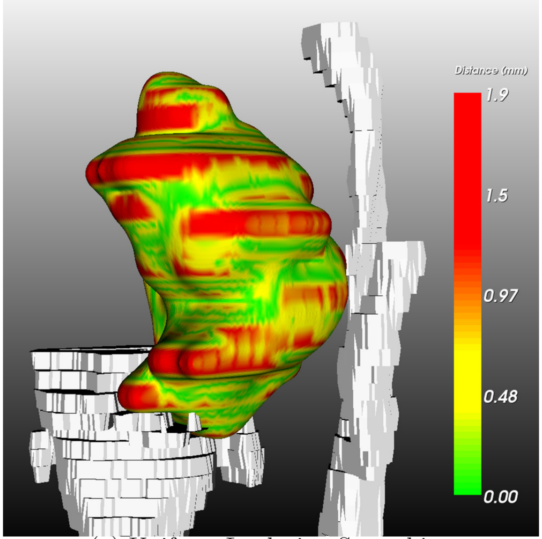
As expected, standard Laplacian smoothing of the tumor model (Fig. 1) yields strong volume shrinkage and distance changes compared to the initial (unsmoothed) surface model and neighboring reference structures (see Tab. 1). On the other hand, the average normal curvature (and thus the terracing artifacts) could be reduced best (curvature decreased from 14.69 degree to 4.02). Other methods, which are focussed on preservation of accuracy, showed better values for distance changes (to the initial model) and volume preservation, but could not produce visually satisfying surface models (see Fig. 4(b) and 4(c)).

The distance-aware smoothing yielded worse Hausdorff distance values than Laplace+HC or smoothing with node position constraint. This is obvious, since these values are reached at parts of the model which have been assigned higher smoothing values because of lower relevance for neighboring structures. The parts of the tumor model, which have been target for distance preservation and thus received lower weighting during smoothing, could preserve the relevant distances to the reference structures (0.35mm and 0.39mm). Furthermore, the average normal curvature has been reduced significantly (7.30 degree). Smoothness is very close to the result of standard Laplacian smoothing (compare Fig. 4(a) and 4(d)), whereas accuracy in terms of spatial relationship has been preserved. The usage of an additional safety margin to define parts without any smoothing gives similar results. However, the visual quality of such a model is slightly worse and the visual difference between smoothed and completely unsmoothed regions might interfere visual perception. Using an exponential scaling function for the distance-aware weighting might be an appropriate tradeoff between a direct usage of the (scaled) distance values and additional safety margins (see Tab. 1).

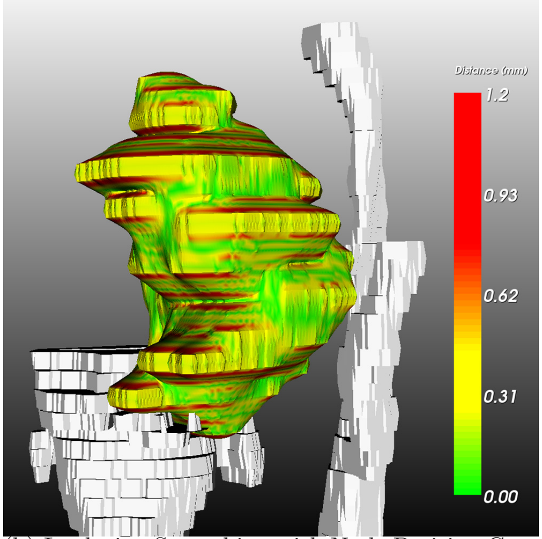
4.2 Model of the Vena Jugularis

The results for smoothing applied to the vessel model (see Tab. 2) with the tumor as spatial reference could basically confirm the results described for the tumor model. Laplacian filtering yields a very smooth surface (curvature reduction from 19.44 degree to 5.43), but introduces very strong errors to the model (3.35mm Hausdorff distance compared to the initial model, volume shrinkage to 81.38%). Laplacian smoothing with node position constraint results in lower Hausdorff distance values, but alters the minimum distance to the tumor model and suffers from volume shrinkage. Laplace+HC produced lower values for the distance measures and shows only slight loss of volume.

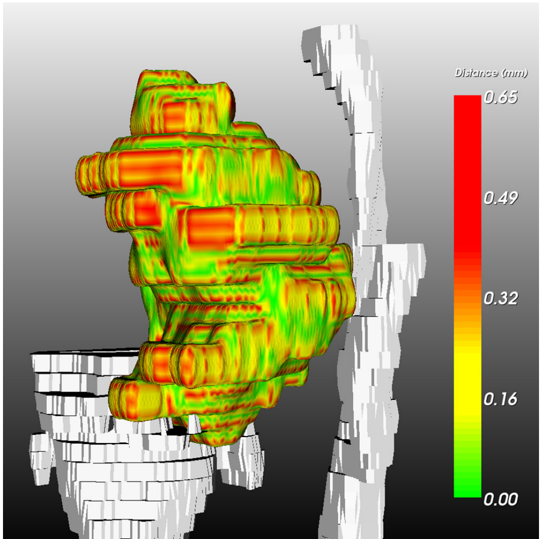
Again, the distance-weighted approaches resulted in worse values for Hausdorff distance (both 2.42mm), but could completely preserve the minimum distance to the reference tumor model. The values, achieved for average normal curvature, showed a strong effect of smoothing (7.37 degree), but applying additional safety margins to the weighting yielded slightly higher curvature values (9.61 degree). The additional application of an exponential scaling function yielded similar values for distance preservation, whereas the volume has been preserved better and the normal curvature values increased slightly (compared to distance-aware smoothing with linear scaling). However, compared to the initial model,



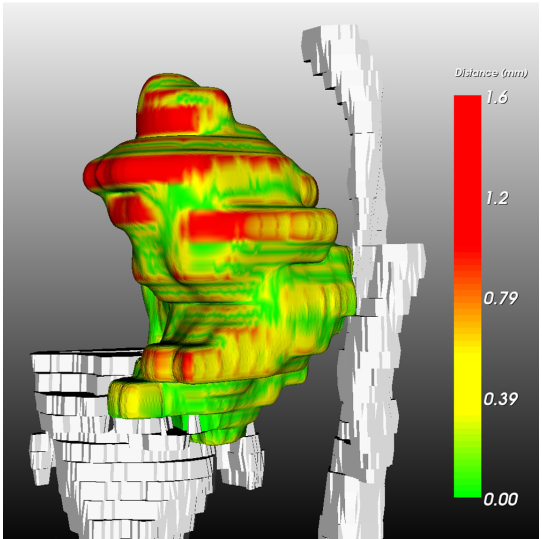
(a) Uniform Laplacian Smoothing



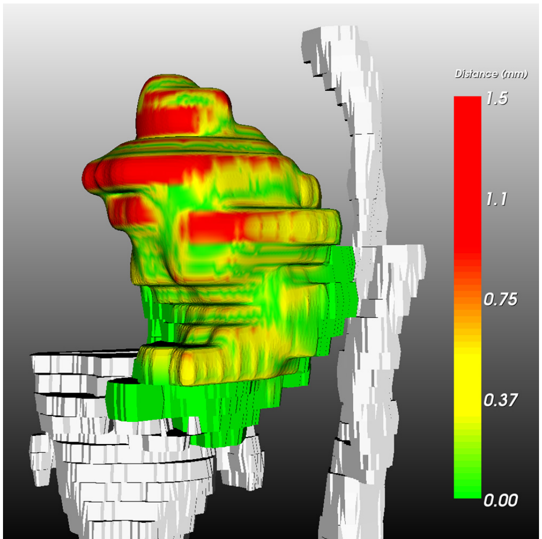
(b) Laplacian Smoothing with Node Position Constraint



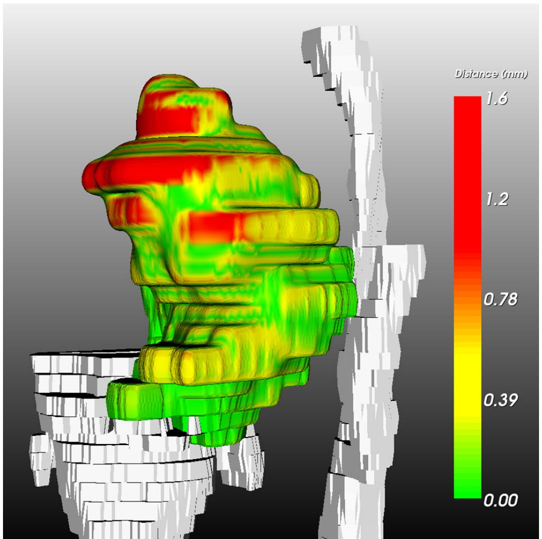
(c) Laplace+HC



(d) Distance-Aware Laplacian Smoothing



(e) Distance-Aware Laplacian Smoothing With 10mm Safety Margin



(f) Distance-Aware Laplacian Smoothing With Exponential Scaling

Figure 4: Sample results of different smoothing methods applied to the tumor model. The surface models are colored by Euclidean distance (in mm) to the original tumor model (without smoothing).

Table 2: Results of a comparison of the smoothed models of the vena jugularis (with the mentioned methods) and the initial MC reference model of the same data. To emphasize the differences between the methods, we applied very strong smoothing with the following parameters (used for all related methods): 20 iterations, λ=1.

Smoothing method	Hausdorff distance to original model (mm)	min. Euclidean distance to tumor (mm)	volume (%)	avg. normal curvature (degree)
Original	0	0.35	100	19.44
Laplace	3.35	1.82	81.38	5.43
Laplace with node position constraint	1.53	1.39	91.86	11.03
Laplace+HC	1.02	0.97	96.71	9.10
Distance-Aware Laplace	2.42	0.35	90.18	7.37
Distance-Aware Laplace (with 10mm safety margin)	2.42	0.35	92.00	9.61
Distance-Aware Laplace (with exponential scaling)	2.40	0.35	94.12	11.56

the effect of smoothing is still sufficient.

5. CONCLUSIONS

Surface models from medical image data often suffer from artifacts, such as staircases and terraces. A reduction of these artifacts can be achieved e.g. via mesh smoothing. However, the properties of the available methods often do not meet the requirements in medical visualization or offer a tradeoff between accuracy and visual quality.

We have presented a modification to standard uniform mesh smoothing algorithms, that allows to gain visual quality in terms of smoothness, since stronger smoothing can be applied, but which preserves relevant inter-structure distances. Distance-aware mesh smoothing can not increase the accuracy of a given surface mesh, but it is suitable to prevent further deterioration during mesh postprocessing. The latter might especially be relevant for the planning of surgical treatment based on segmented medical structures, which already introduce a decrease in accuracy compared to the original anatomical structures (e.g. caused by image acquisition, image preprocessing and segmentation, mesh generation). Furthermore, such a non-uniform surface smoothing might completely alter the shape of the structure, if it is applied too extensively. Thus, the parameters should still be chosen carefully to guarantee, that features in parts of the model being rated less important (for spatial relations) are still preserved.

The application to the model of the vena jugularis showed, that elongated and thin objects are very sensitive to smoothing. Thus, of the employed methods, Laplace+HC gave the globally best results. Though our method has been combined with standard Laplacian smoothing without any restrictions to node positioning or back correction for volume preservation, relevant distances between neighboring structures and the local volume have been preserved. Strong errors have only been introduced at parts of the model which have been treated as less relevant. Adjusting the scaling function for the distance values produced the best tradeoff for application of Laplacian smoothing and volume/distance preservation. As a result, for long and thin objects, an adaptive smoothing approach which is additionally sensitive to vessel diameter, branchings or end caps might improve the results and might be more suitable for application within a surgical workflow.

In the scope of this work, we used a linear increase of the weighting parameters with increasing distance. However, other kinds of scaling functions might be appropriate to preserve inter-structure distances, but to allow for slight smoothing of these areas to gain a visually consistant smoothness over the whole surface model. Furthermore, it is conceivable to involve more information than just spatial relations to the weighting. That could allow to preserve the main extents of a structure or to involve user-specified regions for less or higher postprocessing.

Discussing these results with our clinical partners confirmed, that our method might be a helpful extension for smoothing of medical surface models within the context of surgical planning. However, for future work, it is necessary to investigate, how human visual perception is influenced by surface models which have not been smoothed uniformly.

6. ACKNOWLEDGMENTS

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