# Automatic Generation of a Geometric Model for Representing the Left Ventricle of the Human Heart

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**Abstract.** We introduce a method to generate a three-dimensional model of the human left ventricle to be used for image segmentation in cardiac SPECT data. The model reflects the smooth surface of anatomic objects by only few points. An initial model is derived from a segmented LV from SPECT of a healthy patient using the Marching Cubes (MC) algorithm. A point distribution method creates a new set of points on the existing surface, which are triangulated to form a new surface. The latter then is locally optimised using quality criteria enforcing smoothness and regularity of the triangles. The motivation of this postprocessing step is to reduce the influence of noise in the MC triangulation and to create a surface that is appropriate for subsequent processing steps. Evaluation showed that models generated by our method are smoother and more regular than the initial model.

## 1 Introduction

A common task in cardiac SPECT data analysis is to obtain quantitative information about malperfused parts of the left ventricle (LV) for diagnosis and treatment. Hence, anatomical information about the LV needs to be supplied for differentiating perfused and non-perfused regions. There are two possible ways to provide information about the anatomy of an object: The first one uses the registration with anatomic images like CT [1] or MRI [2], the second one employs a model representing the anatomical knowledge [3]. This paper presents a method to create anatomical models of the LV to be used in the latter strategy.

The models are created from SPECT images of healthy subjects because the model shall be registered with the LV as it appears in SPECT. Reconstruction algorithms for SPECT are known to non-linearly dilate the structures and cause a different appearance of the LV as compared to images from modalities such as CT. Although the functional signal in images of healthy patients coincides with anatomy, it suffers from noise and low spatial resolution. The influence of noise is suppressed in our model by generating a smooth surface consisting of nodes connected to triangles which are sparsely distributed over the LV surface.

Our method is based on an initial model geometry generated from a Marching Cubes triangulation [4] of LV data using an iso-surface value. An iterative node sparsification and redistribution method of [5] is adapted by defining constraints that enforce smoothness and closeness to the original model surface. The model is intended for the representation of a deformable model that has been developed to automatically register with patient-specific SPECT of the LV [3]. The deformable model requires a surface with evenly distributed surface points and a pre-specified resolution of the representation in the range of the data resolution. The model currently employed in [3] (which we will use as a reference to measure the success of our method) fulfills these requirements only in part as it is neither smooth nor guarantees regularly shaped surface elements. Hence, we expect better segmentation results by replacing the reference model.

## 2 Related Work

Surface models to aid image segmentation by a priori information often use a point distribution model where shape variation is trained from sample data [6]. If training is not feasible a model can be generated using a single dataset as prototype data. Shape variation is then defined a priori, e.g. by specifying a physically-based deformation such as in [3].

Since our shape model is a result of the Marching Cubes triangulation remeshing is required for removing influences from noise and reducing the spatial resolution of the model to that of the original data. A survey of remeshing techniques can be found in [7] or [8]. There are two basic ways of remeshing: the first addresses redundancy and oversampling, hence it focuses on mesh simplification (also referred to as fine to coarse remeshing). The second is geared towards improving mesh quality in terms of sampling, regularity or triangle quality (coarse to fine remeshing). Mesh simplification approaches are able to reduce the information by a factor of 50 or even more which is not necessary in our application where resolution should only be reduced by a factor of 3 to 4. Hence, we concentrate on the second strategy.

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Coarse to fine remeshing techniques can be subdivided into isotropic and anisotropic mesh producing methods. Anisotropic meshes do not optimise towards equilateral triangles. Regularity of surface triangles is necessary to apply the deformable model approach of [3] for which our model generation is intended to be used. Isotropic remeshing techniques can be grouped in five categories depending on their goal [7]. Methods of the first two categories generate regular or common connection patterns. Methods of the third category generate regular element shapes, vertex distributions and smooth samplings. Methods of category four and five are geared towards preservation of sharp features as well as error minimizing techniques to conserve maximum similarity.

Methods of category three are the most appropriate for our application, as we do not want to preserve the original surface (which is influenced by noise in the original data), but generate a smooth surface of well-shaped triangles. We adopted the re-tiling algorithm [5] to fit our purpose as it is well-suited for organic structures without displaying sharp features founded on a randomly driven point distribution. Other methods of this category such as e.g. [9], [10] or [11] could be used as well. However, they are more geared towards exact shape preservation which is unwanted if noise influences the initial mesh.

## 3 Model Generation

The model generation method is based on re-tiling by Turk [5]. His method uses a physically driven point distribution for remeshing. New surface points are randomly placed on the input mesh. Each of these points exerts a force on its neighbour points which causes repulsion of the points on the mesh surface. After a defined number of iterations the points approximate uniform distribution. They are triangulated under preservation of the topological structure of the input mesh. The triangulated surface then replaces the original mesh and the process is repeated until a sufficient mesh quality is reached.

Since the re-tiling method was designed for tasks in computer graphics, where the initial model exactly represents the surface with arbitrary spatial resolution, it has been modified to suit the generation of sparse meshes from noisy data. The greedy triangulation of [5] has been replaced by a constrained Delaunay triangulation. The point distances which are used to calculate the repulsion forces are computed through the geodesic path instead of projecting the points on a plane and measuring the distance. This has already been proposed by [5] but had not been implemented because of limited computing power at this time. Both modifications lead to a higher precision in coordinate calculation.

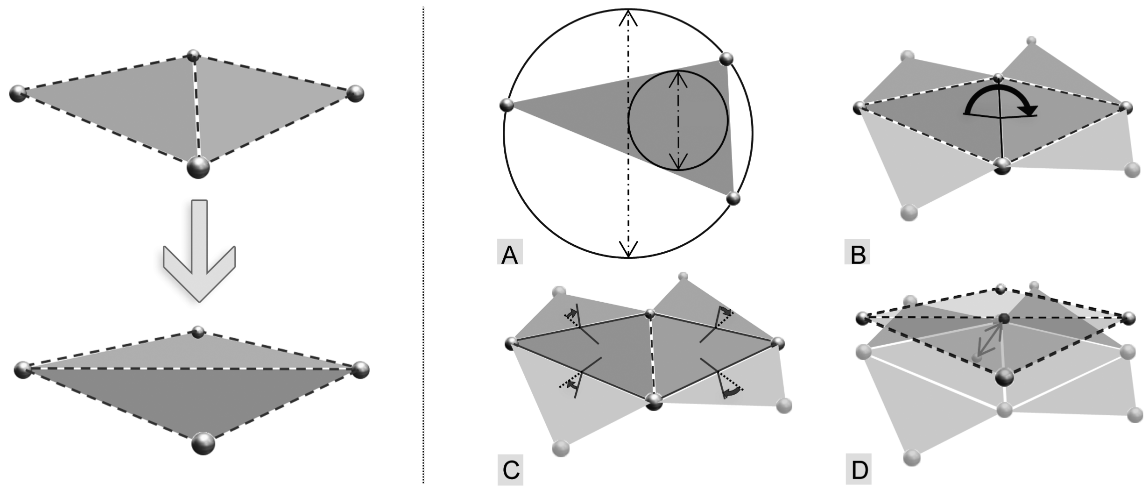


**Figure 1.** On the left hand side a configuration of two triangles in 3D is shown. Below the configuration has been edge-flipped. On the right hand side the fitness criteria A-D are illustrated.

After triangulation further enhancement is achieved by a local triangle optimisation which is carried out on triangle configurations. A triangle configuration consists of two triangles sharing a common edge. The configuration is changed by flipping this edge (see Figure 1 on the left). The edge-flip is carried out, if the alternate configuration leads to better results. This evaluation is performed using a fitness function with four different quality criteria (see Figure 1 on the right):

- angle between the two configuration triangles representing local smoothness ($A$)
- average angle between configuration triangles to all neighbouring triangles representing local smoothness ($B$)

- triangle aspect ratio computed from outer and inner triangle circle ($C$)
- distance from the midpoint of the flipping edge to original surface ($D$)

The angle criteria control the local surface smoothness of the triangle mesh. The triangle aspect ratio is used to obtain triangles with balanced edge proportions. The distance criterion ensures the generation of a mesh surface which is close to the original surface. The latter is important if a small number (<100) of points is used to represent the new mesh.

The quality criteria are weighted (using $w_1$ to $w_4$ normalised by their sum $w_{all}$ and $p$ denoting a configuration of two triangles) in the fitness function:

$$F_{fit}(p) = \frac{w_1}{w_{all}} \cdot \frac{1}{A(p)} + \frac{w_2}{w_{all}} \cdot \frac{1}{B(p)} + \frac{w_3}{w_{all}} \cdot \frac{1}{C(p)} + \frac{w_4}{w_{all}} \cdot \frac{1}{D(p)}. \quad (1)$$

Configurations for edge flipping are selected following a greedy strategy. First, quality improvement for each possible configuration is computed and a list of configurations is created ordered by the improvement value (algorithm 1). Then, edges are flipped for the configurations offering the largest improvement. Configurations affected by this flip are deleted from the list. This procedure is repeated until no further improvements can be found (algorithm 2). Although this process does not guarantee an optimal solution with respect to the overall fitness, it considerably improves the quality of the inital mesh.

**Algorithm 1** Evaluate

**Input:** triangle mesh $M$
**Output:** List with triangle pairs which have improved fitness with flipped edges, ordered by amount of improvement

```
for all p ← pairs of triangles in M do
    f_current ← F_fit(p);
    swapEdges(p);
    f_swapped ← F_fit(p);
    if f_swapped > f_current then
        δ ← f_swapped − f_current;
        List ← (δ, p);
    end if
end for
List.sortDesc();
```

**Algorithm 2** Flipping Edges

**Input:** triangle mesh $M$
**Output:** Mesh with improved surface quality

```
while List ← Evaluate(M) not empty do
    for all pairs p in List do
        swapEdges(p);
        deleteOccurences(List, p);
    end for
end while
```

## 4 Evaluation

Two kinds of evaluations have been performed:

- The generated models have been tested with respect to the initially stated requirements of surface smoothness and triangle shape.
- The performance of the models for LV segmentation have been compared to manual expert segmentations. A spring-mass system [3] has been used to register the models with image data through deformation.

For the model evaluation we used different models generated from four different datasets. Two datasets resulted from thresholded, reconstructed patient datasets showing a healthy heart without perfusion defects, one dataset was a manual segmentation image created for a reconstructed patient dataset, and one dataset was a reconstructed phantom. For evaluation of the performance of the model in segmentation 14 cardiac datasets from patients and one phantom dataset have been used where manual segmentation by an expert served as a gold standard. All datasets have a spatial resolution of $128^3$ voxel.

To evaluate the generated models (Figure 2 b-d), the average fitness value of the whole model is computed at different stages, namely the optimised model after the remeshing step and after the triangle optimisation. Models with a different

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

**Figure 2.** (a) shows the Marching Cubes representation. The models in (b), (c) and (d) are using 110, 150 and 200 sample points respectively, and were created from (a). (e) shows the geometry of the reference model used in [3].

amount of points are created to examine the relation between quality and mesh point density.

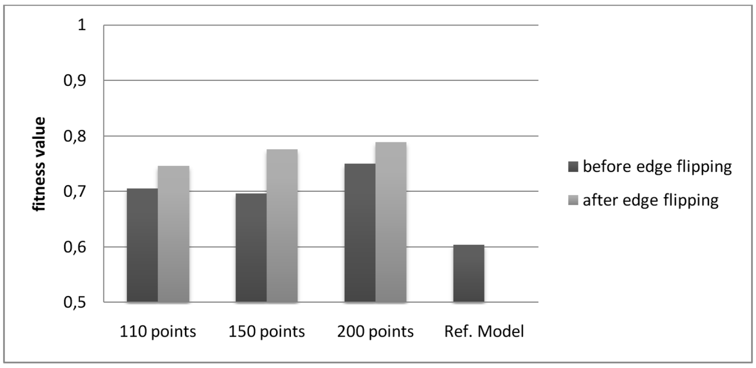


**Figure 3.** This chart shows the fitness value of models differing in the number of points used and evaluating the two conditions after remeshing and after edge flipping optimisation.

The graph in Figure 3 shows that our models achieve better overall fitness values as the reference model. In addition, the postprocessing triangle optimisation improves the fitness of the models up to 11.5% compared to the remeshing result after applying Turk's algorithm [5].

To compare achieved segmentation results with predefined manual segmentations, two measurements are employed. The Jaccard Coefficient is volume-based and denotes the ratio between the intersection and the volume covered by both segmentations A and B:

$$E_J(A,B) = \frac{|A \cap B|}{|A \cup B|}. \tag{2}$$

The second measure is the average contour distance between segmentations, where the smallest distances between the contour voxels of two segmentations A and B are determined and divided by the total number of voxels. $d(a,b)$ denotes the Euclidean distance of two points $a$ and $b$:

$$E_{CD}(A,B) = \frac{\sum_{a \in A_{con}} \min_{b \in B_{con}} d(a,b) + \sum_{b \in B_{con}} \min_{a \in A_{con}} d(b,a)}{|A_{con}| + |B_{con}|}. \tag{3}$$

The impact of the number of mesh points on the segmentation result is examined. Multiple models with different resolutions have been created from the same template dataset. They were used to segment the 14 evaluation datasets. Results of the first evaluation dataset are shown examplarily in Table 1. Tendentially no differences could be found in the remaining evaluation data.

| **number points** | **67** | **110** | **150** | **200** | **300** | **Ref.-Model (67 p.)** |
|---|---|---|---|---|---|---|
| $E_J(A,B)$ | 0.662 | 0.751 | 0.758 | 0.748 | 0.649 | 0.663 |
| $E_{CD}(A,B)$ | 0.382 | 0.293 | 0.261 | 0.351 | 0.410 | 0.424 |

**Table 1.** Evaluation results of the segmentation using models sampled with different numbers of points for patient dataset 1.

If the model had a number of points that was equal to those of the reference model results of the distance criterion were better. The quality is improved further if the number of surface points was increased to 100 to 200. The usage of more than 200 points leads to more springs connecting the points with each other. This damps the adaptation process accomplished by the spring-mass system resulting in poorer segmentation results. Altogether both evaluation criteria are showing that new models with an appropriate number of points are able to achieve considerably better segmentation results than the reference model.

## 5 Conclusions

An approach to generate 3D models to represent the left ventricle in cardiac SPECT data has been introduced. It uses a modified point distribution and sparsification method based on the re-tiling method of [5] to create a new mesh from a Marching Cubes representation. A new weighted triangle optimisation technique is employed for improving the mesh surface quality of the original algorithm. Evaluation results show that our approach considerably improves the quality of the model surface in comparison to the reference model. The main application of the models is the segmentation of the left ventricle to quantify malperfused areas. The evaluation also shows that segmentation results compared to the formerly used reference model could significantly be improved. In addition to multiple models for testing purposes we created four models which are (at present) sufficient to segment all datasets. In case that new reconstruction methods are introduced there may be the need for new models.

An extension to the re-tiling algorithm has been implemented to enhance the surface smoothness in areas of higher curvature. The point forces for the repulsion, which is used to evenly distribute points on the initial surface, are dynamically adapted to the local curvature at each point. As a result, the point density in more curved regions is higher. Hence, local smoothness can even be produced in coarser object representations. As a future work, this technique can be refined and the impact on the deformation process has to be investigated more thoroughly.

A further future investigation could be to expand the method to work on other organs like kidney or liver, which have very similar characteristics compared to the LV.

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