A Novel Approach to Segmentation of Coronary Arteries in MR Images for Computational Fluid Dynamics (CFD) Simulations

P. Makowski[1,2], S. Ringgaard[2], E. T. Fruend[2], E. M. Pedersen[2]

[1]Institute of Electronics, Technical University of Lodz, Lodz, Poland, [2]Institute of Experimental Clinical Research and MR Centre, Aarhus University Hospital, Aarhus N., Denmark

Synopsis

The abstract presents a novel approach to the segmentation of coronary arteries in MR images. The result of the segmentation in form of a triangular mesh (STL) represents the surface of the vessel. The 3D STL model has been used as geometric boundary condition for Computational Fluid Dynamics (CFD) simulations of velocity flow patterns and wall shear stresses in the right coronary artery. The model of the coronary artery is represented with a set of ellipsoids or spheres with centers along the vessel axis. The segmentation procedure is based on marking the position of each ellipsoid center and their radii. The vessel surface is represented as a triangular mesh covering all ellipsoids. The entire process consists of: positioning "key ellipsoids", interpolation of automatically added ellipsoids between the key ones, conversion to a discrete binary image, isosurface triangulation and surface smoothing.

Introduction

In order to understand the mechanism of atherogenesis in the coronary arteries, numerical simulations of flow velocity profiles and wall shear stress (WSS) based on non-invasive magnetic resonance (MR) boundary conditions is a promising approach. The most important step in numerical simulations is the generation of realistic boundary conditions such as the vessel geometry. Models of the vessel wall, used for CFD simulations, are usually created as a set of splines [1]. However, this is not a fully universal method as modeling of some complex vessel junctions is difficult or even not possible. In this abstract we present an alternative and more universal method.

Material and method

A typical image dataset used for segmentation was acquired on a Philips Intera MRI scanner with a phased array cardiac coil using an ECG triggered and navigator gated gradient echo sequence (hybrid segmented k-space and EPI 3D sequence, 0.8 x 0.8 x 2.0 mm resolution, EPI factor 13). Segmentation started with defining location of centers of "key ellipsoids" along the axis of the artery. The key ellipsoids were positioned at the beginning and the end of each branch and in places with high curvature.

The developed software provides the user with a cross sectional view of the MR images in each of the three orthogonal planes, and the locations of the ellipsoids can be set in each plane. The user can view the MR images of the vessel in additional cross-sectional planes, perpendicular to the vessel axis. This opens the opportunity to precisely locate the center of each ellipsoid on the additional plane and set its radius. In the segments of low curvature additional ellipsoids are inserted automatically and each ellipsoid's position and radius is interpolated from the key ones. This gives a set of dense, overlapping ellipsoids (Fig.2). This set is converted to a binary image as a logical sum (an "OR" function) of the internal regions of all ellipsoids. Ellipsoids overlap in the internal region of the vessels and at the junctions of the branches, creating a continuous, solid region. In the next step a surface of the binary image is constructed as an isosurface triangulation [2]. The regularized marching tetrahedra algorithm is used as a method giving a regular surface. As we use a simplified triangulation algorithm the resulting mesh of triangles is smoothed using a deformable model algorithm, but alternative ways of surface smoothing can be also used.

Results

The presented method allows the creation of a triangle mesh (STL) representing small arteries (as the coronary arteries) with complex vessel junctions. The first two segmentation phases based on user interaction could be completed within approx. 40 min. The speed of the remaining segmentation process depends on the voxel to triangle size ratio. For a ratio of 4, the model generation phase took 5 min, and surface smoothing 7 min on a 2 GHz processor. The resulting mesh was used as boundary condition for numerical simulations of velocity profiles and WSS using the methods described in [3].

Conclusions

The main limitation of the method is the manual determination of location and radii of the key ellipsoids. This approach was chosen because the low spatial resolution of the images relatively to the vessel size makes the use of automatic methods difficult and unreliable and intensive manual corrections are always required. The implemented visualization tools make the manual process quite efficient. Use of the OR function renders the method much more universal than methods involving splines and opens the potential for use of other shapes than ellipsoids, which could be used in modeling shape deformation or vessel prostheses, e.g. stents. It also allows combination with other segmentation approaches, which can produce binary regions as each of the resulting regions can be combined with the OR function.

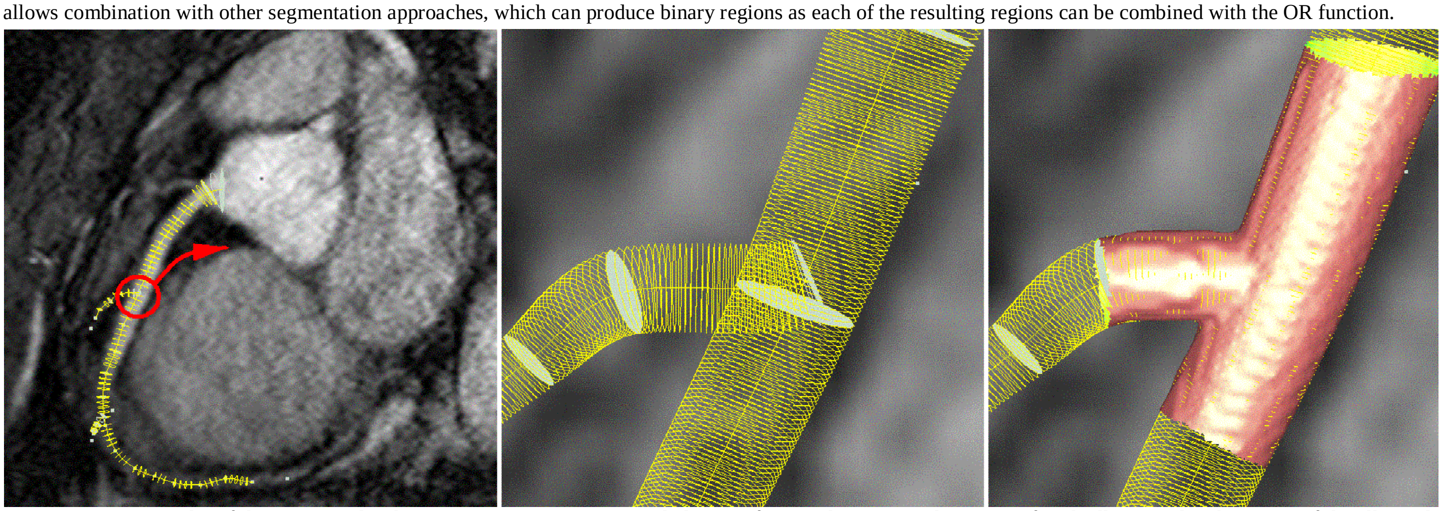

Fig. 1. MR angiography of the segmented right coronary artery. Fig 2. Detailed view of a vessel junction. The center of each ellipse is also the center of the ellipsoids used in the OR function. White disks denote position of the key ellipsoids. Fig 3. Detailed view of the rendered surface covering the vessel junction.

[1] M. Oshima, K. Takagi, Y. Ichijo - Summer Bioeng. Conference, Sonesta Beach, Florida, 2003.
[2] G.M.Treece, R.W.Prager, A.H.Gee - Computers and Graphics 1999 pp.583-598.
[3] E.T. Fruend, C.Baltes, P.Makowski et al. - ISMRM Toronto 2003 p.1626.