Vessel Tortuosity Extraction from IVUS Images

D Rotger[1], P Radeva[1], O Rodriguez[2]

[1]Computer Vision Center, University Autonoma of Barcelona, Spain
[2]University Hospital Germans Trias i Pujol, Badalona, Spain

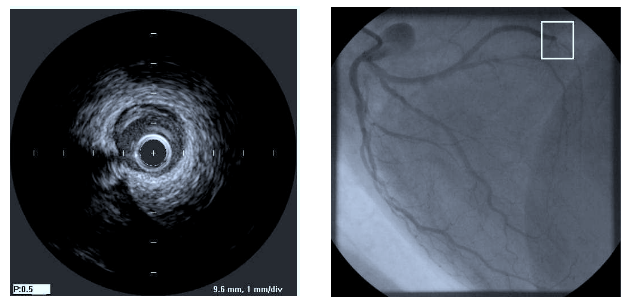
Abstract

When looking at an IntraVascular Ultrasound (IVUS) pullback image data, the lack of three-dimensional information does not allow to know the real shape of the vessel we are observing, and thus to infer whether the plaque is more probable to be deposited. The main objective of this work is to establish a mechanism to infer vessel extreme curvature points from the position of the IVUS catheter inside the blood vessel observed in the IVUS images without any external information. The obtained curvature is validated with its real 3D shape reconstructed using a system we developed before that fuse IVUS and angiography images[1]. We will see that the results are promising, partially revealing the extreme curvature points of the vessel. For the first time, vessel curvature can be partially extracted from IVUS images without any external information. This opens a wide range of possibilities like predicting plaque formation and the fusion with other modalities as optical computer tomography.

1. Introduction

Intravascular ultrasound images have allowed deepening in the knowledge of the true extension of the coronary vessel illness. It is a tomographic image that provides a unique 2D *in vivo* vision of the internal vessel walls (figure 1.a), determining the extension, distribution and treatment of the atherosclerotic, fibrotic plaques and thrombus, and their possible repercussion on the internal arterial lumen. Angiography images provide an external vision of the vessel shape and tortuosity (figure 1.b). The main advantage of the ultrasound compared to the angiography images, deals with the fact that the most of the visible plaque lesions with IVUS are not evident with angiogram.

One of the problems of dealing with IVUS is the fact that the images represent an 2D plane perpendicular to the catheter without any depth information. This IVUS property hides the real disease's extension and represents a very unnatural way of conceptualization. The foremost limitation of IVUS on the pre- and post-treatment studies is the lesion images correlation in the serial studies. This limitation is due to the lack of the third dimension that



(a) (b)

Figure 1. (a) IVUS image. (b) Angiography of a vessel with stenosis.

gives much more global information about the internal and external vessel structure.

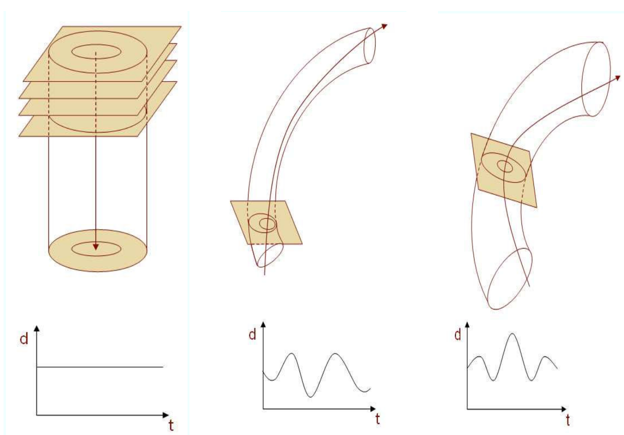
In clinical practice it is very common to have to register several IVUS pullbacks performed to the same blood vessel of the same patient, like in follow-up studies, atherectomy, stent implantation and other procedures. Nowadays, this problem is solved mainly in two ways: the first is the use of vessel branches, visible by IVUS, and matching them in both sequences; the second way is by using the information given by the angiographies as explained at [2, 3, 4, 5]. Using two angiogram projections and taking into account the calibration parameters, we are able to create a curve in the space, representing the vessel curvature and tortuosity, where placing the IVUS images.

The main motivation of this work is the limitations of both techniques. The use of visible branches entail some problems of ambiguity (more evident in follow up studies), imprecision and it is a very time consuming procedure. The second procedure is more reproducible and precise, but it is also time consuming and it implies a more controlled environment and the use of a well calibrated angriographic machine at every imaging procedure.

Our hypothesis is that points of extreme curvature can be robust landmarks to register IVUS sequences (at least, may complete and speedup bifurcation location procedures). We will see that it is possible to detect extreme curvature points without any external information from other imaging modalities, only looking at the position of the IVUS catheter inside the blood vessel.

2. Methods

Our hypothesis is that the plot of the Euclidean distance between the catheter center and the nearest tissue point will show a different profile depending on the curvature of the vessel at each point and on the sectional area of the lumen at that point. In figure 2 we can see the three different profiles that can appear. Figure 2(a) shows the profile of a straight vessel; we can see it corresponds to a straight line given the catheter can freely be pulled back while the blood pressure and the guide wire will keep it as straight as possible. Figure 2(b) signs how the profile may change when looking to a curved thin vessel. We can see that the catheter goes a little far from the vessel wall in the surrounding sections of the point of curvature where the distance is minimal. The opposite happens in the case of a thick vessel, given the catheter has more space so its tip (not the transducer position) can easily reach the opposite wall allowing the transducer to navigate in the central part of the vessel, see figure 2(c).



(a) (b) (c)

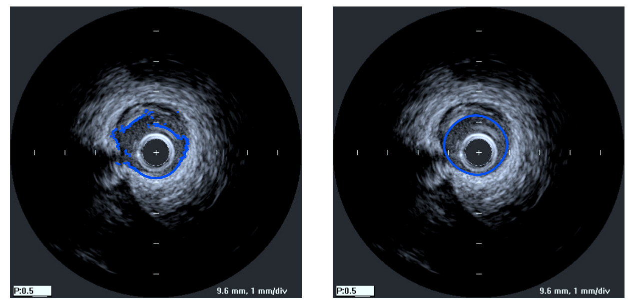
Figure 2. Vessel shapes and their distance profiles to the vessel wall: (a) straight, (b) thin and (c) thick vessels profiles.

The first thing we need to do in order to be able to measure the distance from the catheter center to the vessel wall is to detect the blood-tissue transition (lumen boundaries). For this purpose, we have trained a neural network with lumen boundary models created by several medical experts.

We use these models to radially determine the gradient in the graylevels in the boundary pixels and its surrounding area. For this purpose we use a polar image representation from the original IVUS (cartesian) one. This polar image is created with its central point (first row) corresponding to the central point of the catheter of the cartesian image and radially to the outside. The gradient values in the area surrounding the models is approximated by a linear equation which parameters are the input for the neural network.

Therefore, lumen boundaries detection is performed by creating the polar image representation of the original IVUS image plane and a radial search for the activations of the neural network.

After the segmentation step, the model is smoothed using a closed BSpline interpolation. Figure 3 shows the segmented image and its smoothed representation using a BSpline model.



(a) (b)

Figure 3. Segmented image using the neural network (a) and its BSpline approximation (b).

3. Validation Procedure

In order to validate that maximal curvature points in the 3D path shape correspond to the points of minimal distance between the catheter center and the lumen borders, we have used the three-dimensional vessel shape reconstructed by a system we developed before that fuse IVUS and angiography images called ActiveVessel described in [1]. Given the obtained 3D curve of the catheter path inside the vessel we calculate its curvature (k) at each IVUS image position $(x(t), y(t), z(t))$, taking into account its correspondence [5], following the next equation:

$$k = \sqrt{\frac{(y'z'' - y''z')^2 + (x''z' - z''z')^2 + (x'y'' - x''y')^2}{(x'^2 + y'^2 + z'^2)^3}}$$

Then, the error in the localization of the maximal curvature point of the vessel is measured as the Euclidean distance (in the space) of the point with maximal curvature k and the maximum/minimum (depending on the vessel sectional area) of the dynamic profile of the center of the catheter with respect to the vessel wall.

4. Results

Our dataset contains 15 IVUS pullbacks by a Boston Sci. Galaxy device performed on 12 different patients containing curved and straight segments. Activevessel workstation protocol was followed during its acquisition to allow three-dimensional reconstruction of the vessel shape.

We compared the dynamic distance profile with the location of maximal curvature of the three-dimensional model extracted by Activevessel as described in the previous section.

In figure 4 we can see the plot of the distance to the vessel wall (in red) and the curvature of the 3D shape (in blue) for three curved thick vessels and figure 5 shows three more plots of tinny vessels. We can easily identify the predicted distance profiles shown in figure 2. The mean error found locating the points of maximal curvature of our dataset have been 1.9mm with a standard deviation of 0.25mm.

In order to make evident the changes in the dynamic profiles depending on the vessel's sectional area, we have also analyzed the behavior of these profiles with vessels that have been dilated with an angioplasty balloon. We can see in figure 6 the plots of three thin vessels before its dilatation and, in figure 7, the results of the same vessels after being dilated. It can be seen that the the plots of figure 6 follow the profile of a thin curved vessel as hypothesized at figure 2(b). But the most important is to see how that profiles change when dilating the vessel (figure 7) and pass to follow the hypothesis of a thick curved vessel of figure 2(c).

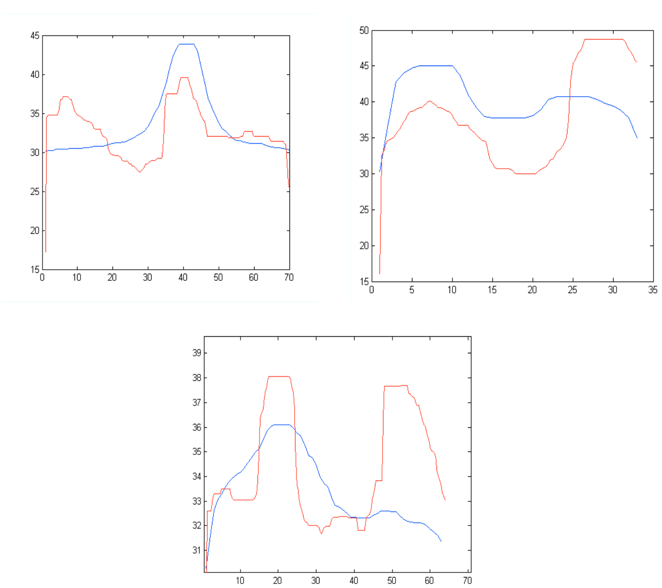


Figure 4. Plots of the distance to the vessel wall (in red) and the curvature of its 3D shape (in blue) for three thick and curved vessels.

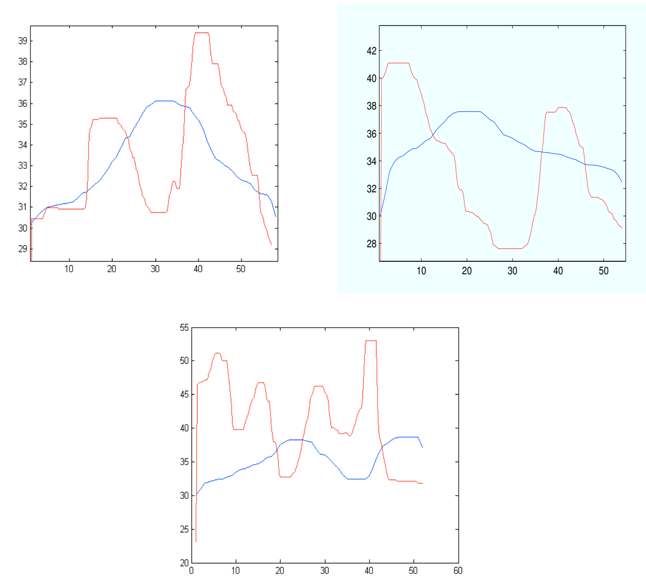


Figure 5. Plots of the distance to the vessel wall (in red) and the curvature of its 3D shape (in blue) for three thin and curved vessels.

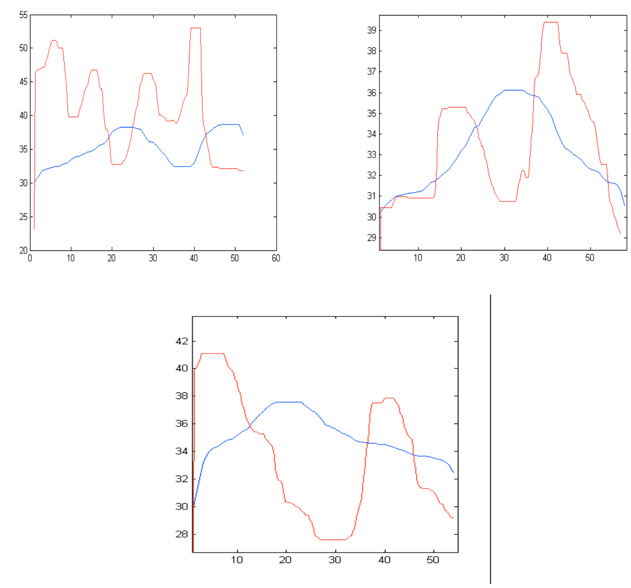


Figure 6. Dynamic profiles of three thin and curved vessels before their dilatation.

5. Discussion and conclusions

We proposed a simple method to detect curvature maxima of the vessel just from IVUS data without any external information only taking into account the position of the catheter inside the vessel and its sectional area.

This information is very useful to predict the localization of possible plaque accumulation points as well to register

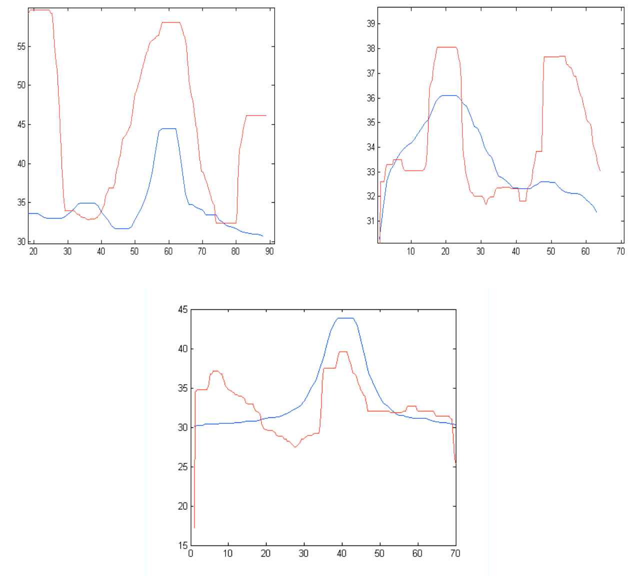


Figure 7. Dynamic profiles of the same three thin and curved vessels of figure 6 after their dilatation.

different pullbacks of the same vessel segment for follow-up studies, atherectomy, stent implantation and other procedures. It can also be used to complete and increase the precision of a registration using side branches.

Even though, it is needed to be said that if exact curvature should be calculated, we need a complete 3D reconstruction fusing IVUS with biplane angiography. More work needs to be done in order to determine the degree and exact localization of these maximal curvature points and the threshold in the sectional area to determine what we a thick or a thin vessel is and to study the transition between both profiles.

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Address for correspondence:

David Rotger Muñoz
Computer Vision Center / Edifici O / Campus UAB
08193, Bellaterra (Cerdanyola), Spain
rotger@cvc.uab.es