

Semi-automatic Measurement of Vessel Wall Support from Implanted Stents in IVOCT Image Sequences

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Abstract. Intravascular stents are devices that are used for supporting vessel walls to improve the blood flow. Intravascular optical coherence tomography (IVOCT) provides very high resolution images which can be used to evaluate the support of implanted stents to vessel walls during the percutaneous coronary intervention (PCI) and at follow up. The stent cell structure is important for stent support analysis and its full size and maximum circular unsupported surface area (MCUSA) are commonly used to measure the degree of vessel wall support. We present two different methods (*A* and *B*) to compute full stent cell area and one method to compute the MCUSA. These methods include stent strut detection and transformation, stent cell detection, stent surface reconstruction, cylinder fitting to stent cells and MCUSA detection. To measure full stent cell size, method *A* uses the reconstructed stent surface, while method *B* uses the cell contours after cylinder fitting. The MCUSA method determines the largest circle in this contour using distance transform. The evaluation on two phantom datasets shows accurate measurements of the stent cells. Based on our phantom data set, the accuracy of methods *A* and *B* are 99.3% and 99.1% respectively and the results from both methods are consistent. The methods were also applied to real IVOCT image sequences for support analysis.

1 Introduction

Coronary stents are widely used to treat coronary artery diseases. During a PCI, a stent is extended by an inflated balloon to support the vessel wall and to keep the vessel open. Clinical research has demonstrated that the support of implanted stents to the vessel wall positively influences the outcome of the PCI [1]. Stents should be flexible and be able to provide enough support. The full size of each cell structure of the implanted stent is one of most common feature used to compute the stent support. Recently, the maximum circular unsupported surface area (MCUSA) was proposed as a new feature to evaluate the stent support [2] and it is defined as the maximal circle area that can be fit inside a stent cell structure.

Stent cell measurements can be used to evaluate the stent design for its distribution after implantation, or to compute the coverage of an implanted stent to side-branches. It also provides the possibility to evaluate the mechanism of controlled drug release from drug-eluting stents as well.

IVOCT is a relatively new 3D optical imaging technique which provides very high resolution (10 – 20 μm) images of the coronary vessels [3]. It is increasingly being

used for the evaluation of stent placement. Because IVOCT images are the tomographic cross-sections of vessels, implanted stents are visible as individual bright spots (struts). IVOCT data can be used for the support analysis of implanted stents by providing precise location of the individual struts. To the best of our knowledge, there is no published method to compute the full cell size or MCUSA of implanted stents in IVOCT image sequences.

The challenging part of the support measurements is to identify the stent cells and to calculate their area in the 3D space. In order to reduce the complexity when identifying the stent cell, we convert the stent strut position from 3D to 2D and keep the conversion mapping, so that the final calculation can be based on the original 3D cell contour. In this paper, we present two different methods to compute the full stent cell size and one method for MCUSA estimation. In section 2, the measurement methods are presented, while the empirical results of two phantom datasets and two real IVOCT datasets are presented in section 3. The analysis of the results is described in section 4 and the conclusions in section 5.

2 Methods

The new approach consists of five parts: (1) stent strut detection and transformation; (2) 3D stent cell contour generation; (3) full cell area measurement method *A*; (4) full cell area measurement method *B*; (5) MCUSA estimation. All the measurements can be performed as the flow chart illustrates in Fig. 1.

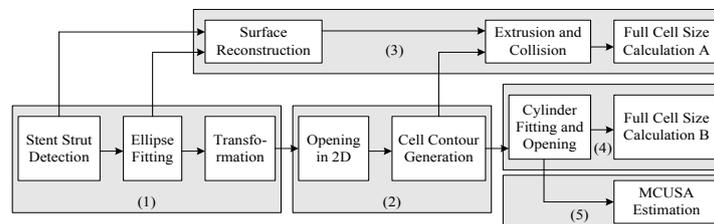


Fig. 1. The flow chart of the implanted stent cell measurement methods

2.1 Stent Strut Detection and Transformation

Bare metal and drug-eluting stent struts can be detected automatically following recently published methods [4, 5, 6]. As Fig.2 (a) shows, the stent center is not the image center, so struts in (b) are transformed and then projected onto the surface of a cylinder like (c) which can be opened in 2D for strut cell recognition.

Because a stent is extended by an inflated balloon in the vessel, its cross-sections are more or less elliptical. Therefore, the stent struts in each frame are fitted with an ellipse using a modified least-squares ellipse fitting method [7]. More struts can lead to better fitting, so the struts from 3 continuous frames are used to fit the ellipse in the middle frame. Infrequently, if there are still less than 5 struts for ellipse fitting, this stent contour will be generated by interpolation. Ellipse centers are transformed to the

center of IVOCT images together with stent struts. After transformation, all the struts can be projected onto a cylinder based on their angles. Each strut in (c) matches the corresponding strut in (d), therefore, after detecting the stent cell from opened stent (e), the original 3D stent cell contour (f) can be generated.

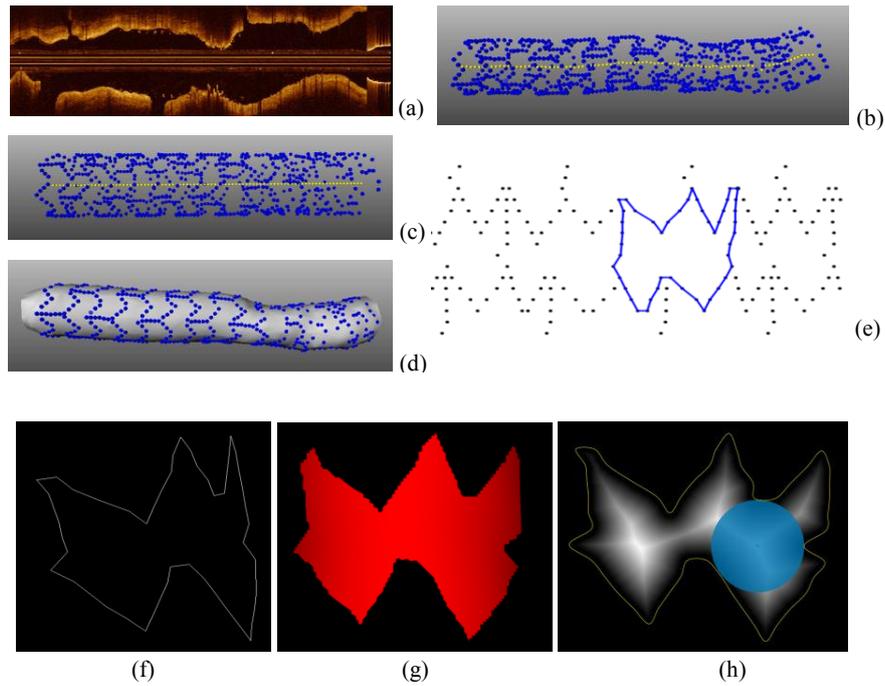


Fig. 2. In (a) a longitudinal IVOCT image is presented and (b) shows the stent struts (blue dots) and the stent contour centers (yellow dots) of a real IVOCT image sequence. Fig. 2(c) shows the transformed and projected struts on a cylinder surface. Fig.2(d) is the reconstructed surface with struts. Fig. 2(e) shows a part of an opened 2D stent with clear cell structures. A stent cell is shown in blue and (f) shows the corresponding 3D stent cell contour; with (g) the selected cell surface piece, while (h) shows the opened cell contour and the detected MCUSA by the blue circular area. The white area is the result of the distance transformation.

2.2 Stent Cell Contour Generation

There is a large variety in the shapes of cell structures of different stents and a stent cell can be distorted during the expansion. Additionally, each stent cell structure consists of many stent struts. Without any a-priori information, it is challenging to classify automatically the struts that belong to each cell. However, after having opened the stent into a 2D mesh as Fig. 2(e), the stent cell patterns can be recognized better. This mesh shows a clear structure but the real area still needs to be derived, so a mapping is required between the struts in the 2D mesh and the struts in the original 3D space.

To generate the stent cell contour, we need to identify the struts that belong to each individual cell. Our method requires the user to observe the pattern in the 2D mesh and then select the struts on the scaffold junctions in the proper order. Usually, it takes about 5 seconds to recognize a stent cell. Users can select two key struts and the struts between these two key struts are found and linked automatically based on the shortest distance. Once all the struts from the 2D mesh are recognized, through the mapping, the corresponding struts in the original 3D space are selected in the same order. Finally, the 3D stent cell contour can be generated by linking the struts using a B-spline. A cell contour is shown in Fig. 2(f).

2.3 Full Cell Size Measurement A

The cell contour defines the cell area of the implanted stent, so the surfaces for the stent cells are generated. With the stent struts detected as described in section 2.1, the stent surface can be reconstructed using the method proposed by Hoppe [8], which can reconstruct an accurate, piecewise smooth surface from a group of points. However, the guide wire can cause breaches on the reconstructed stent surface, since no information can be collected in its shadow area. In this case, we fill this blank gap with artificial points on the fitted stent ellipse. With the guide wires detected by strut detection method [4] and the fitted ellipse from section 2.1, imaginary points are added on the ellipse arcs behind the guide wires. It should be noted that any stent cell that contains such artificial points cannot be used for measurements. They only support the stent surface reconstruction to compute the other cells.

Next, the cell surface can be selected using 3D stent cell contours. The cell contour may not exactly be located on this stent surface, because the interpolated points on the contour can be located above or below the stent surface. To solve this problem, the cell contour can be projected on the surface and then the cell area can be cut from the surface. For projection, the cell contour is extruded to generate a hollow object to intersect with the stent surface. The contour extrusion direction and length is indicated by a calculated vector. The vector is orthogonal to the centerline of the stent and passes through the center of the boundary box of the stent cell contour. The collided part is selected from the stent surface as the cell surface using VTK [9] as Fig.2 (g) shows. It is represented by many small triangles and its area can be calculated by summing the areas of these triangles.

2.4 Full Cell Size Measurement B

A second method B to calculate the full size of stent cells was also implemented by fitting the stent struts with a cylinder. However, to fit the whole stent to a single cylinder can introduce big errors, because stents can be bended or distorted during the placement. In order to reduce the errors that are introduced by cylinder fitting, we only use the struts belonging to one stent cell instead of all the struts. Because the cell struts do not cover the whole surface of the cylinder, we need to use a good guess for initialization to guide the cylinder fitting in case it fails. The guessed initial cylinder has the same origination and the radius as the whole fitted cylinder. The fitting is

based on the least-squares method [10] which can minimize the sum of the absolute distance between struts to the fitted surface.

After cylinder fitting, the stent cell is opened into 2D as Fig. 2 (h) shows. Compared to the opening in section 2.1, this time the real stent cell area is reserved. Attention is paid to this procedure, because it may separate the stent cell into two halves. If the opening starts from the middle of the stent cells, we need to rotate the start position to the outside of the stent cells. Besides, the new resolution of the opened contour should be calculated. The pixel size in the angle-axis direction should be calculated from the radii of fitted cylinders, while the pixel size in the cylinder orientation direction should be calculated based on the angle of cylinder orientation. With the size of each pixel, the full size of the opened stent cell can be calculated.

2.5 MCUSA Estimation

MCUSA is the maximal circle that can be fitted inside the opened 2D stent cell from section 2.4. It is usually used together with the full cell size during the research for stent support analysis. The center of MCUSA should be the point that has the maximum shortest distance to its surrounding boundary. We first generate an image from the 2D cell contour and then apply a distance transformation algorithm. The pixel having the highest intensity should be the center of the MCUSA and the intensity value is the maximum shortest distance. There may be more than one maximum circle, but they all have the same size. Using the pixel size from section 2.4, the size of MCUSA can be calculated.

3 Evaluation

All the IVOCT image sequences that we have tested were acquired with a C7-XR frequency-domain OCT intravascular imaging system using a C7 Dragonfly imaging catheter (LightLab Imaging, Inc., Westford, MA, USA). During the imaging, blood was flushed with contrast medium. The pullback speed was 20.0 mm/s and the frame rate was 100 frames/s. Two randomly selected polar IVOCT image sequences were used in our research. One data set contains a guide wire while the other one does not. The image sequence size is 960 pixels \times 504 pixels \times 271 frames and they were converted into 1024 pixels \times 1024 pixels \times 271 frames Cartesian image sequences. After the conversion, the axial resolution is 6.85 μ m and the distance between the frames is 0.2 mm.

A phantom data set was generated by scanning a 3.0 \times 8.0 mm coronary stent using Micro-CT. The CT data set also contains cross-sections of stent as the IVOCT, but with higher resolution. Its size is 1024 pixels \times 1024 pixels \times 1240 frames with a voxel size of 5.86 μ m \times 5.86 μ m \times 6.62 μ m. In this phantom data set, the extended stent is almost a cylinder of which the average diameter is 3.0 mm and has a length of 8.2 mm. By fitting the saw-shape part in one side of the stent to the saw-shape part in the other side, we can treat this stent as a cylinder. The saw-shape part is about 0.8 mm, so the new cylinder length is 7.4 mm. The stent surface area is about 69.7mm².

Due to its high resolution, stent cell results from method *B* were used as the ground truth. To estimate whether methods *A* and *B* work accurately on data sets with the same slice distance as IVOCT, we re-sampled the phantom data set with the slice distance of 0.2 mm (one frame out of every thirty frames).

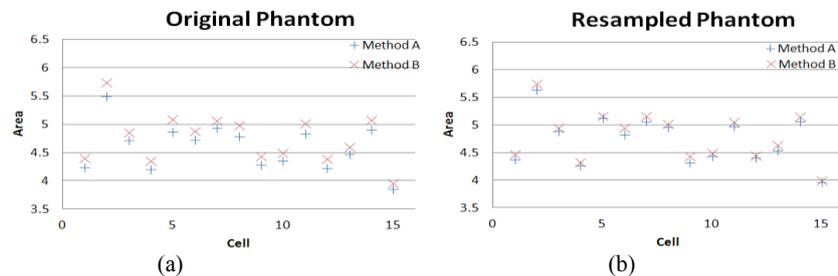
Table 1. Maximum value, minimum value, mean value with standard deviation and the sum of the stent cell size from method *A*, *B* and MCUSA measurement. Original dataset is the phantom dataset with all slices. Resampled dataset is the phantom dataset with fewer frames, so that it has the same slice distance as real IVOCT data sets.

Data set	Method	Max (mm ²)	Min (mm ²)	Mean \pm SD (mm ²)	Sum (mm ²)
Original dataset	<i>A</i>	5.50	3.85	4.59 \pm 0.41	68.82
	<i>B</i>	5.74	3.96	4.75 \pm 0.44	71.27
	MCUSA	1.70	0.95	1.29 \pm 0.22	19.28
Re-sampled dataset	<i>A</i>	5.64	3.97	4.72 \pm 0.44	70.77
	<i>B</i>	5.74	3.99	4.79 \pm 0.45	71.90
	MCUSA	1.70	0.87	1.25 \pm 0.22	18.76

Table 2. Maximum value, minimum value, mean value with standard deviation and the sum of the stent cell size from method *A*, *B* and MCUSA measurement. IVOCT1 contains a bioabsorbable stent without guide wire, IVOCT2 contains a metal stent and a guide wire.

Data set	Method	Max (mm ²)	Min (mm ²)	Mean \pm SD (mm ²)	Sum (mm ²)
IVOCT1	<i>A</i>	3.78	1.00	2.54 \pm 0.78	137.11
	<i>B</i>	3.96	1.07	2.66 \pm 0.79	143.40
	MCUSA	1.40	0.25	0.76 \pm 0.30	40.87
IVOCT2	<i>A</i>	2.92	1.39	2.20 \pm 0.43	22.01
	<i>B</i>	3.00	1.45	2.30 \pm 0.45	22.97
	MCUSA	1.21	0.52	0.86 \pm 0.25	8.55

Stent struts from both original and re-sampled phantom data sets were detected automatically. First, our methods were applied to the original phantom dataset to compute the ground truth. Next, the methods were tested on the re-sampled phantom dataset that has the same slice distance as IVOCT to determine the possible changes in performance. As a last test, our methods were evaluated with two clinical IVOCT datasets.



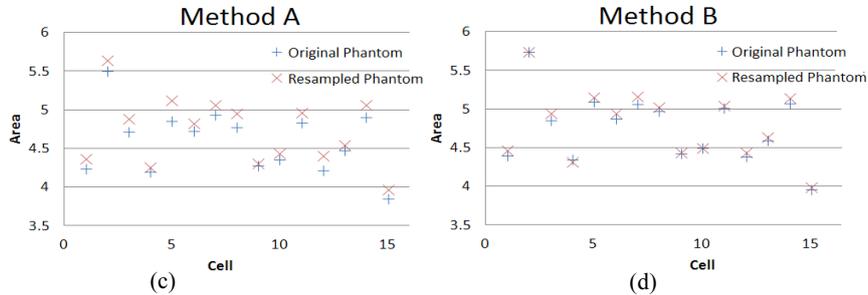


Fig. 3. (a) shows the results of method *A* and *B* for the cell in the original phantom data set, and (b) the results from methods *A* and *B* for the re-sampled phantom data set. (c) shows the results from method *A* for the corresponding cells in both original and re-sampled phantoms, while (d) compares the results from method *B* for the corresponding cells in original and re-sampled phantoms

4 Analysis and Discussion

Table 1 shows that the ground truth of the whole stent surface area from method *B* is 71.27 mm^2 and the estimated result from method *A* is 68.82 mm^2 . They are both close to the theoretical value (69.7 mm^2). Table 2 shows the quantitative analysis results of the cell area of the two clinical implanted stents. Compared with the original phantom data set, our methods present almost the same results from the re-sampled phantom data set. It suggests that our methods could be used to calculate the stent cell size in real IVOCT image sequences.

Fig. 3 shows that the results from method *A* are usually a little smaller than the ground truth results from method *B*. A possible explanation is that method *A* calculates the full cell size from the reconstructed stent surface that consists of thousands of small triangles, while method *B* calculates the stent cell using the opened surface from cylinder. For a curved surface, the opened surface should be bigger than the surface with triangle polygons.

Because the distributed stent struts do not fit to any common shape in 3D space, it is difficult to get the ground truth of cell area. Our methods provide an intuitive approximate measurement of the stent support to vessel walls.

IVOCT image sequences provide the longitude image data of the implanted stent along the imaging catheter. In practice, the imaging catheter may be bent with different angles. Without the 3D tracking of the imaging catheter, the cell area in IVOCT data may contain an error when the imaging catheter bends. However, in most cases, the trajectory of the imaging catheter has only smooth curvatures so that the error for distortion should be limited. Therefore, this method is expected to give out a good approximation of the stent cell area.

5 Conclusion and Future Work

The proposed methods can compute the full cell size and the MCUSA accurately for the support analysis of implanted stents. First a full resolution phantom dataset and its resampled dataset were used to evaluate the feasibility and the accuracy of our methods. Next, our methods were applied to two real IVOCT datasets. Quantitative evaluation results reveal that the methods have achieved high accuracy for the stent cell structure measurement and can be used for stent support analysis.

After automatic stent strut and guide wire detection, the imaginary stent contours are aligned using the stent centerline and then opened as a 2D mesh. This compensates for the difference in catheter position in the vessel during the pullback. Stent cells are then generated using this stent mesh.

In the future, we will work on stent distortion corrections, such as cardiac motion, take the width of the stent wire into account, detect the stent cell fully automatically and test our methods with more IVOCT data sets. We also plan to use these methods to calculate the coverage of the implanted stent to the side-branches.

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