AN ENHANCED ALGORITHM FOR OPTIMAL CATHETERSELECTION DURING CORONARY ANGIOGRAPHY

A. Khalil, S.U. Rahman, F. Alam, H. Khalil* and K. Gulati**

Department of Computer Science and IT, University of Malakand, Pakistan
*Department of Mathematics. University of Education, Attock Campus, Pakistan
**School of Computer Science and IT, Stratford University, USA
Corresponding author's email: fakhrealam@uom.edu.pk

ABSTRACT: Image processing based catheter selection is an advanced technique in which three dimensional (3D) curve of the coronary arteries and aorta were projected on a two dimensional (2D) plane and the parameters were estimeted. During the projection of 3D curve to 2D plane there was information loss which affected the final results. In present study, an algorithm for selecting an optimal plane which reduced the information loss during the projection phase was suggested. The proposed method was evaluated on the ground truth and the obtained intraclass correlation coefficients and their 95% confidence intervals had the confidence limit between 0.996 –1.00. The results showed that the proposed method minimized information loss during projection. It minimized mean error in angle calculation to 2% as compared to the existing algorithm that had 6% error rate. The proposed method was time efficient and it estimated the parameters from the patient image data on optimal plane.

Keywords: Angiography, Catheter, Image processing, Optimal plane and Right coronary artery.

(Received 22-10-2016 Accepted 15-12-2017)

INTRODUCTION

Angiography is a medical imaging technique for the visualization of heart vessels (Yang*eet al.,* 2013; Balaji and Shah, 2011). Process of angiography is performed by a small incision made in the upper thigh and a guide wire is inserted into the femoral artery which is threaded towards the aorta (Taner *et al.,* 2013). A catheter is then inserted along the guide wire and is passed into the coronary arteries (de Vecchi *et al.,* 2014). In the next step, the contrast material is injected through the catheter and is added to the blood in the small vessels. The anatomy of the aorta and coronary arteries is usually different in different humans, therefore, the same type of catheter cannot be used for every patient. Currently, there are two methods used for the selection of catheter during coronary angiography:1) trial and error based and 2) image processing based.

In trail and error based method, the cardiologists test different catheters for a patient and select the best catheter according to the patient's anatomy. Trial and error based approach is time consuming and there is also a possibility of damage to the artery if the catheter is not properly matched to the patient's internal anatomy. Image processing based catheter selection is a newly developed method in which a catheter is selected before the physical intervention (Rahman *et al.,* 2015). In this method, the optimal catheter is selected on the basis of the internal anatomy of the patient's coronary arteries (Flehmann *et al.,* 2011; Rahman *et al.,* 2011a; Rahman *et al.,* 2011b). This advanced method of optimal catheter selection reduces the risks of testing several catheters on a patient and also reduces the operating time.

The existing method of image processing based optimal catheter selection generates a 2D plane from some points on centreline image, but there is no information about data loss due to the projection of the curve on the plane. Therefore, the estimated results of the existing method are also ambiguous. In present study, an algorithm is suggested which minimizes information loss by computing optimal plane for projection. The proposed algorithm needs segmented image and centerline image to extract the coronary artery curve. The method then estimates the optimal plane from the different projection plane and uses that optimal plane for the parameters estimation to select a catheter for coronary artery angiography.

An existing method proposed by (Rahman *et al.,* 2011b) for optimal catheter selection is enhanced by introducing a new step called optimal plane selection. The proposed step finds a plane for projection of the coronary arteries curve on which information loss is minimum. Theproposed method is time efficient and it estimates the parameters from the patient image data on optimal plane. The proposed method is evaluated on the ground truth and the obtained intraclass correlation coefficients and their 95% confidence intervals have the confidence limit between 0.996 –1.00. These are given in a high level of agreement between the manual and automatic measurements.

MATERIALS AND METHODS

In the proposed method, the segmentation of aorta and coronary arteries was performed with the developed algorithm (Flehmann *et al.,* 2011). The algorithm segmented the aorta and coronary arteries in the MR cardiac images as shown in Figure-1 (a). For extracting centerline of the aorta and coronary artieries a binary thinning algorithm developed by (Homann 2007) was used. The centerline image of the segmented image is shown in Figure-1 (b).

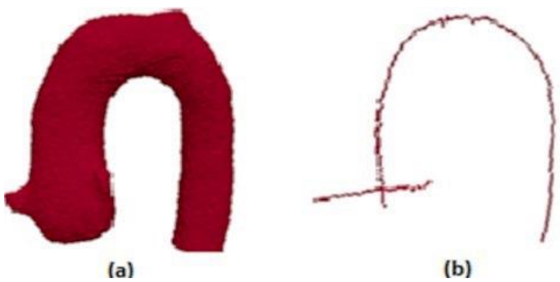

Figure-1: Segmented image and centerline image of the aorta and coronary arteries. (a) segmented image (b) centerline of the aorta and coronary arteries.

The centerline image of the patient was used to find the right coronary artery (RCA) curve which consist of points between P_0, P_m and P_{n-1} as shown in Figure-2 (b). In the Figure, P_{n-1} is the tip of the coronary artery, P_m is the branching point of the aorta and coronary artery and P_0 is the midpoint of the aorta. The adopted methodology for curve extraction started from a search pointer that moved on the centerline image from down to top. The search pointer continued until it determined more than two non-zero pixels in the same slice as shown in Figure-2 (a), this point was the starting point D for finding the rest of the curve. The starting point is denoted by D through which the rest of the curve could be determined. Figure-2 (b), shows four points i.e., E, P_0, P_m and P_{n-1} on the centreline image of aorta and coronary artery. Point E is the highest point of the aorta estimated from point D. Po is the midpoint of point D and E is estimated from the average of their indexed values. P_{n-1} is the tip of right coronary artery which showed its starting point and is estimated from point D. The Point P_m remains fix during the calculation of parameters for optimal catheter selection. In Figure 2(b), P_m is the branching point of the aorta and coronary artery. P_m is calculated by moving search pointer from P_0 downwards and computing non-zero neighbor pixels. In this process, if the value of non-zero neighbor pixels were more than one and a point with greater x-axis index value was considered as a point P_m. Therefore, a curve which calculates the angle between aorta and coronary artery was obtained from the points among P_0, P_m and P_{n-1} as shown in the Figure-2 (b).

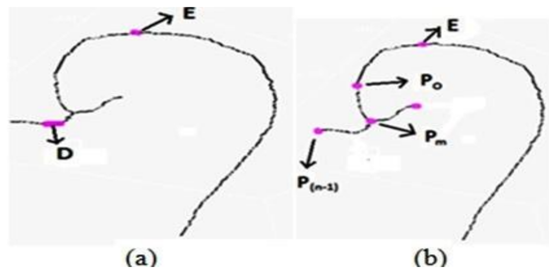

Figure-2: Coronary artery curve angle computation. (a) represents the initial and the highest point on cenetline image (b) shows mid point, branching point and tip of coronary artery on centerline image

In the proposed method, after the extraction of the coronary artery curve of the centerline image, the next step was to select the optimal plane for the projection of the curve.

To create a plane from points P_0, P_m and P_{n-1}, a unit normal was determined on the basis of which the relation between points and plane was obtained. The equation of the unit normal for the plane was $\hat{n} = \overleftarrow{P_0P_m} \times \overleftarrow{P_mP_{n-1}}$, therefore, a relation for all the points denoted by Pr on the projection plane S0 was obtained. The relationship of the unit normal of the plane and the projected points on projection plane is shown in equation 1.

$$S_0(x, y, z) = P_0P_r.\hat{n} \qquad (1)$$

The next step was to find the projection of the original curve on the plane S_0. The new set of projected points on this plane were labeled as $P_i^0 = (x_i^0, y_i^0, z_i^0)$, where $i = 0{:}\, n-1$. The main idea behind the above process was to find the difference between the original and projected curve. Equation 2 calculate Ψ_0 which was the average difference between the original curve and projected curve on plane $S_{0.}$

$$\Psi_0 = \sum_{i=0}^{n-1} \frac{\sqrt{(x_i - x_i^0)^2 + (y_i - y_i^0)^2 + (z_i - z_i^0)^2}}{n} \qquad (2)$$

Although plane S_0 was used to calculate the angle and length of coronary artery and aorta, but one cannot surely say that the obtained result was precise or not. It was due to the variability in the structure of coronary artery and aorta for each patient. Therefore, the same process was repeated to calculate the same parameters on another plane S1 which was obtained from points P_0, P_m and P_{n-2}as shown in equation 3.

$$\Psi_1 = \sum_{i=0}^{n-1} \frac{\sqrt{(x_i - x_i^1)^2 + (y_i - y_i^1)^2 + (z_i - z_i^1)^2}}{n} \qquad (3)$$

In equation 3,Ψ_1 represent the avarage difference between the original curve and curve plotted on the plane S1.

In the proposed method, average difference between the original curve and projected curve on all possible planes was determined . It is represented by Ψ_j, as shown in equation 4.

$$\Psi_j = \sum_{j=0}^{n-1} \frac{\sqrt{(x_i - x_i^j)^2 + (y_i - y_i^j)^2 + (z_i - z_i^j)^2}}{n} \text{for } j = m + 1 : n - 1. \quad (4)$$

Where xi, yi and zi are the original curve points and $x_i^j x_i^j x_i^j$ are the points projected on plane Sj where j=m $+ 1: n - 1$.

In the proposed method, the final point was placed on Pm and it remained unchanged until the calculation of all the possible planes by moving every point from P_0 to Pm-1. Thus $\Psi_k$was obtained as shown in the equation 5. The obtained Ψ_k is the average difference between the original and projected curve on every plane from P_0 to Pm-1.

$$\Psi_k = \sum_{k=0}^{n-1} \frac{\sqrt{(x_i - x_i^k)^2 + (y_i - y_i^k)^2 + (z_i - z_i^k)^2}}{n} \text{for} k = 0 : m - 1 \qquad (5)$$

By adding Ψ_j and Ψ_k, $n - 2$ values of$\Psi_i$were obtained which the difference between the original curve and projected curve on all possible planes as shown in equation 6.

$$\Psi_i = \Psi_j + \Psi_k \qquad (6)$$

After the estimation of differences in all possible planes, the final step was to select an optimal plane. The optimal plane depended on the value of Ψ_i because if the value is minimum, more accurate parameters would be estimated. Mathematically, it is shown in equation 7.

$$\text{OptimalPlane} = S_r \because |\Psi_r| \le |\Psi_i| \forall\ i = 1 : n - 2. \qquad (7)$$

This optimal plane was used for the precise calculation of angle and length of the specified coronary artery curve.

After the selection of optimal plane, the next step was to calculate the parameters of the right coronary artery (RCA) curve. For this (RCA) angle was calculated as shown in Figure-3. Figure-3 (a) shows the projected curve on optimal plane while Figure-3 (b) shows the tip of coronary artery represented by A, a branching point B and point C which was lying on the mid of aorta. In part (c) of Figure-3, the vectors obtained from points A, B and C were described. These vectors were used to calculate the angle of aorta and coronary artery.

All the points were projected on optimal plane, which were in 3D Space. Therefore, points A and B were convrted to vector $\overrightarrow{AB}$ and points B and C to $\overrightarrow{BC}$. Conversion of point A, B and C to vector $\overrightarrow{AB}$and $\overleftarrow{BC}$was performed if the coordinates of A, B and C were$[x_1, y_1, z_1]$, $[x_2, y_2, z_2]$ and $[x_3, y_3, z_3]$ respectively. This is shown in equation 8 and 9 and the graphical representation of Vector $\overrightarrow{AB}$ and $\overleftarrow{BC}$ are shown in Figure-3 (c).

$$\overrightarrow{AB} = [x_2 - x_1, y_2 - y_1, z_2 - z_1] \qquad (8)$$

$$\overrightarrow{BC} = [x_3 - x_2, y_3 - y_2, z_3 - z_3] \qquad (9)$$

The length of the coronary artery curve was an important parameter in the image processing based optimal catheter selection. An optimal plane was used to calculate the length of coronary artery. To calculate the length of coronary artery, the distance between point B and point C was measured, as shown in Figure-3 (c). In the Figure, (a) shows the projected curve on optimal plane while (b) shows the tip of coronary artery represented by A, a branching point B and point C which is lying on the mid of aorta. In Figure (c), the vectors obtained from points A, B and C are described.

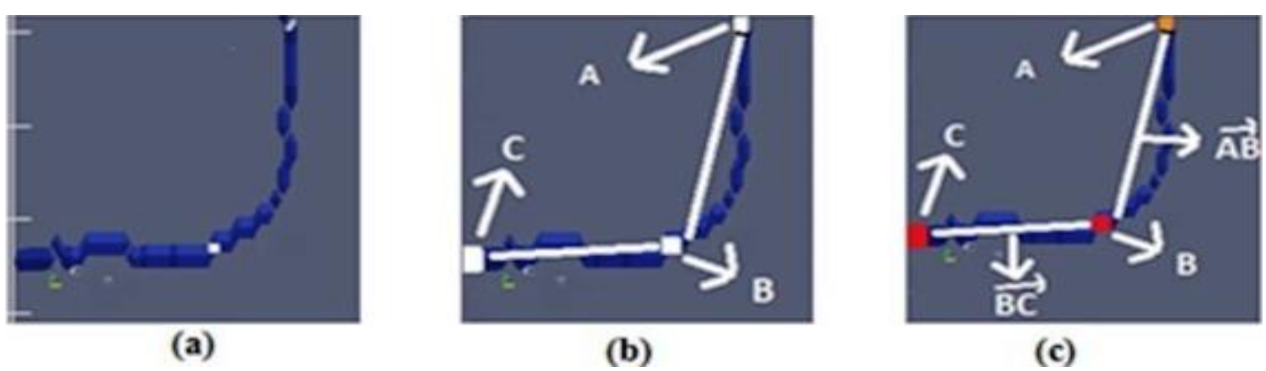

Figure-3. Projected curve on optimal plane and methodology of parameters (a) projected curve on optimal plane, (b) tip of coronary artery represented by A, a branching point B and point C. Figure (c), the vectors obtained from points A, B and C.

To assess the accuracy of the proposed method, estimated parameters were compared with the manual computations obtained by three experts. All the experts were experienced in the medical imaging field. Seven

MR data sets of patients were obtained from our clinical partner. Three dimensional cardiac images (3D) of sizes $150\times150\times150$ pixels were used for all the experiments.

In order to measure the different parameters from the centerline image of the patients, segmented image of coronary artery and aorta, and centerline image in (Inc, K., 2006) was displayed. The opacity of the segmented image was kept high while that of centerline image was kept low. This enabled the centerline image to be visible in the segmented image, as shown in Figure-4. To find out the coronary artery curve angle, 3D image in Figure-4 was rotated and adjusted in VTK according to the best possible visual view of the curve angle in the image. In the next step, the VTK angle widget was used to calculate the angle between the aorta and coronary artery. The experts then selected three points of the VTK angle widget on the image in which the first point was placed on the tip of a coronary artery, the second point on branching position while the third point was placed on the aorta (Figure- 4). Table 1 shows the estimated paramters from the patient's image data. In the experiments an average of the estimated paramters was taken to create a ground truth.

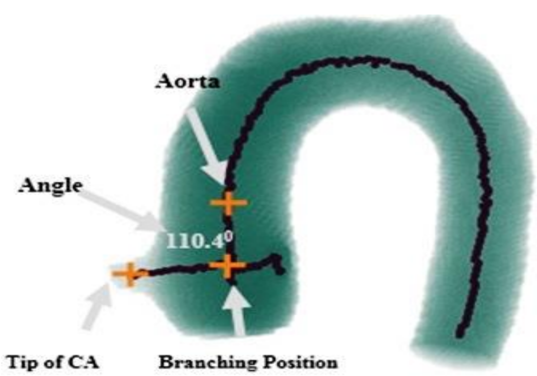

Figure-4. Manual method for the calculation in coronary artery and aorta angle

Table-1: Coronary artery curve angle computation results from experts parameters estimation method and existing method. The angle of CACA is calculated in degree.

No	Expert 1	Expert 2	Expert 3	Mean of the Three experts (Ground Truth)
1	111.3	110.3	113.2	111.6
2	149.2	152.2	150.2	150.5
3	122.2	123.2	124.2	123.2
4	93.2	96.2	90.2	93.2
5	115.1	113.1	116.1	114.7
6	93.1	97.1	91.1	93.7
7	156.2	154.2	156.2	155.5

RESULTS AND DISCUSSION

The experiments were carried out on Intel core i5 with 4 GB memory, running under the Windows 7 operating system. The algorithm was implementd in C++, the Insight Registration and Segmentation toolkit (Johnson *et al.*, 2013) and visualization toolkit (Kitware, 2015). The algorithm was tested on 3D MR cardiac images of seven patients having sizes of $150\times150\times150$ pixels, obtained from clinical partner. In the proposed algorithm, three points were randomely considered on the curve and created seven different planes and projected the curve on these planes. Table 2 shows the angle calculation for a single patient data using the different planes.

Table-2: Different calculated angles and projection error (Ψ_i) on different plane.

Projection plane	Coronary artery curve angle (degrees)
1	120
2	121
3	125
4	126
5	129
6	133
7	138

The projected curve on these plane resulted in variations in angle computation. These results showed that random plane selection may produce worst results. In the next step of experiments, the results prodcued by algorithm were compared with the results of the existing algorithm.

To evaluate the accuracy of proposed method with the existing method, the comparision was performed using the coronary artery curve angle and computation time required to extract parameters. Table 3 shows the obtained parameters using the manual method, existing method and proposed method. It is shown in the Table that the proposed method produced more accuracy than the existing method due to the optimal plane. In Table 3, mean value of the expert for patient 1 was 111.6, the result of the proposed method for patient 1 was 110:20 and existing method result was 105:30. Results of proposed method was more near to the ground truth than the exiting method.Table 4 shows the time comparisonof both the methods. The proposed method required more processing time than the existing method because of optimal plane selection in the image.

Table-3: The computed parameters using manual method, existing method and proposed method

No	Ground Truth	Existing Method	Proposed Method
1	111.6	105.9	110.3
2	150.5	134.8	152.2
3	123.2	120.1	123.2
4	93.2	100.2	96.2
5	114.7	123.1	113.1
6	93.7	100.2	97.1
7	155.5	139.2	154.2

Table-4: Comparison of execution time of existing method and proposed method.

Data Set	Execution Time (in second) of the proposed algorithm:	Execution Time(in second)of the existing algorithm
Patient 1	2.133	1.322
Patient 2	2.486	1.892
Patient 3	3.261	1.43
Patient 4	2.891	1.11
Patient 5	2.014	1.9
Patient 6	2.925	1.43
Patient 7	3.23	1.78

Image processing based optimal catheter selection for coronary artery angiography was an advance technique which extensively reduces the risks of catheterization. The existing work on image processing based optimal catheter selection was presented by (Rahman, 2012; Flehmann *et al.*, 2011; Rahman *et al.*, 2011b; Rahman *et al.*, 2011a). In their work, the algorithms suggested that the projection plane should be created from any three points on the coronary arteries curve. In the existing methods, a 2D plane was generated from some points on centreline image, but there is no information about data loss due to the projection of the curve on the plane. Moreovere, the results generated from the existing methods were also ambiguous.

In this study, we have presented an image processing based optimal catheter selection method for coronary angiography. The proposed computerized method was fully automatic which selected an optimal plane for the projection of coronary arteries and calculated the angle and length of the coronary arteries. Selecting an optimal plane for the projection of coronary arteries curve was important for calculating accurate angle and length of the coronary artery.Optimal plane selection ensured the accuracy and correctness of the estimated parameters. Accuracy in the angle and length of the coronary artery was highly desired for optimal catheter selection during angiography. The proposed method was tested on seven MR images of different patients and compared with the existing method and manual method. The results showed that the proposed method compute the parameters more accurately due to optimal plane selection.

However, the proposed method required more time to extract parameters from the patient image data as compared to existing method, which was the limitation of the proposed method.

Conclusion: In this paper, we have presented an algorithm for selecting an optimal plane which reduces the information loss during the projection phase in image processing based catheter selection during coronary arteries angiography.

REFERENCES

Balaji, N. and P. Shah (2011). Radial artery catheterization. Circulation. 124(16): 407–408.

Bland, J.M. and D. Altman (1990). A note on the use of the intraclass correlation coefficient in the evaluation of agreement between two methods of measurement. Comput. Biol. Med. 20(5): 337-340.

De Vecchi, A., R. E. Clough, N.R. Gaddum, M.C. Rutten, P. Lamata, T. Schaeffter, D.A. Nordsletten and N.P. Smith (2014). Catheter-induced errors in pressure measurements in vessels: an in-vitro and numerical study. IEEE Tran. Biomed. Eng, 61(6): 1844-1850.

Flehmann, E., S. Rahman, S. Wesarg and W. Voelker (2011). Towards patient specific catheter selection: computation of aortic geometry based on fused MRI data. International Conference on Functional Imaging and Modeling of the Heart (FIMH): 145-152.

Gu, W. J and J. Liu (2014). Ultrasound-guided radial artery catheterization: a meta-analysis of randomized controlled trials. Intensive Care Med: 40(2): 292-293.

Homann, H. (2007). Implementation of a 3D thinning algorithm. InSight, 421,

Inc, K. (2006). The VTK User's Guide: Updated for Version 5: Kitware.

Johnson, J. Hans, M. McCormick and L. Ibáñez (2013).The Insight Software Consortium. The ITK Software Guide. Kitware, Inc., Third edition, In press.

Rahman, S., A. Khalil and F. Alam (2015). A Review on Image Processing Based Optimal Catatheter Selection in Coronary Angiography, J. Cardiovasc.Dis. 13 (1): 23-27.

Rahman, S., S. Wesarg and W. Völker (2011a). Patient specific optimal catheter selection for the left coronary artery. Emerging Technologies for Medical Diagnosis and Therapy: 119-117.

Rahman, S., S. Wesarg and W. Völker (2011b). Patient specific optimal catheter selection for right coronary artery. Proc. SPIE 7964, Medical Imaging 2011: Visualization, Image-Guided Procedures, and Modeling: 224-230.

Rahman, S. (2012). An image processing based patient-specific optimal catheter selection, Universitäts- und Landesbibliothek Darmstadt.

Taner, M. T., G. Kagan, S. Celik, E. Erbas and M.K. Kagan (2013). Formation of Six Sigma infrastructure for the coronary stenting process. International Review of Management and Marketing, 3(4): 232-242

Wang, Y. and P. Liatsis (2009). A fully automated framework for segmentation and stenosis quantification of coronary arteries in 3D CTA imaging. Second International Conference on Developments in eSystems Engineering (DESE): 136-140.

Yang, Q., K. Li, B. Sun, H.Yun, L.Tang, S.Li and L.Jin (2013). Assessment of coronary artery disease using 3.0 T magnetic resonance coronary angiography: a national multicenter trial. J. Cardiovasc. Magn. Reson. 15(1):E5.