CHAPTER 3

Assessment of Obstruction Length and Optimal Viewing Angle from Biplane X-ray Angiograms

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Assessment of obstruction length and optimal viewing angle from biplane X-ray angiograms.
Shengxian Tu, Gerhard Koning, Wouter Jukema, Johan. H.C. Reiber
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ABSTRACT

Three-dimensional quantitative coronary angiography (3D QCA) has been encouraged by the increasing need to better assess vessel dimensions for the diagnosis and for support of interventional procedures. A novel 3D QCA system based on biplane X-ray angiograms is presented in this paper. By correcting for the isocenter offset and by improving the epipolar constraint in the correspondence of the two angiographic projections, accurate and robust reconstruction of the vessel centerline is achieved and the reproducibility of its applications is guaranteed. The accuracy and variability in the assessment of obstruction length and bifurcation optimal viewing angle were investigated using phantom experiments. The segment length assessed by 3D QCA correlated well with the true wire segment length ($R^2 = 0.999$) and the accuracy was $0.04 \pm 0.25 \text{ mm (} P < 0.01)$. 3D QCA slightly underestimated the rotation angle (difference: -1.5° ± 3.6°, $P < 0.01$), while no significant difference was observed for the angulation angle (difference: -0.2° ± 2.4°, $P = 0.54$). In conclusion, the new 3D QCA approach allows highly accurate and precise assessments of obstruction length and optimal viewing angle from X-ray angiography.
3.1 INTRODUCTION

Accurate interpretation of vessel dimensions from X-ray angiography is of great importance to the diagnosis of cardiovascular diseases and to support coronary interventions. Two-dimensional quantitative coronary angiography (2D QCA) has been widely used to obtain clinically relevant parameters, e.g., obstruction length and diameter stenosis, and to assess the results of PCI-trials [1]. However, due to the perspective deformation of vessels on the projection images, 2D QCA has inherent limitations in interpreting the true dimensions of the vascular structures, resulting in an increasing interest in the research and development of three-dimensional quantitative coronary angiography (3D QCA) systems [2-6].

Restoring 3D morphology of the vascular structures requires at least two projections. Biplane angiograms supply a nice solution to the reconstruction problem by allowing two projections obtained at the same time. However, the 3D reconstruction from two projections is an underdetermined problem, allowing a huge number of feasible solutions which could satisfy the projection data [5]. In addition, mechanical distortions in the X-ray systems, as well as noise corruption in the projections, make the development of reliable and robust 3D QCA systems a non-trivial task.

The accuracy of 3D QCA systems mainly depends on the reconstruction of the vascular structures, of which the centerline reconstruction is the primary and yet the most important step. Once an acceptable solution for the 3D centerline has been obtained, the issue of reconstructing the cross-sections becomes relevant. To determine the exact position of the 3D centerline points, the correspondence between the two projected centerlines should be established first, mainly by using the epipolar constraint, i.e., the constraint between a projection point and its corresponding epipolar line, being the projection of the X-ray beam directed towards a particular point on one of the projection planes onto the second projection plane [5]. However, the isocenter offset, i.e., the spatial displacement of the isocenters in the frontal and lateral systems, together with the small perspective viewing angle, i.e. the angle between the epipolar line and the arterial centerline, for noise-corrupt arterial centerlines, could greatly deteriorate the epipolar constraint, leading to an inaccurate correspondence.

Many efforts [2-4, 6] have been undertaken to correct for the isocenter offset, either by manually or automatically identifying several reliable points, e.g., anatomical landmarks, as reference points on the two projections and involving the epipolar constraint [5] to approximate the isocenter offset. At least 5 to 8 pairs [3] or 2 to 5 pairs [7] of reference points were needed to approximate the isocenter offset. However, it may
be very difficult in routine clinical practice to find that many reliable reference points in the two projections, due to the presence of vessel foreshortening and overlap. In addition, requiring the user to indicate many reference points is not very attractive from a workflow perspective. To guarantee the accuracy and reliability in this interactive procedure has already been a difficult task.

We have been very interested in developing a fast and reliable system for the reconstruction of vascular centerlines from X-ray angiography. To minimize the number of reliable reference points in the correction of the isocenter offset and yet to achieve a good correspondence in the centerline reconstruction, we proposed to use one to three reference points for the correction of the isocenter offset. In case of the presence of small perspective viewing angles for noise-corrupt arterial centerlines, the usage of epipolar constraint was further improved by building a distance transformation matrix and subsequently by searching the optimal corresponding path in the matrix. The reconstructed vessel segments can then be used to assess obstruction (stenotic lesion) length and bifurcation optimal viewing angle. In the following sections, the methodology will be presented, followed by the applications of centerline reconstruction in assessing obstruction length and bifurcation optimal viewing angle; next, the validation approach will be described, followed by the results, the discussions and the conclusions.

3.2 Methods

3.2.1 Image geometry

The conventional biplane angiographic equipment consists of a frontal X-ray system and a lateral X-ray system. In theory, the frontal projection axis (central beam) intersects with the lateral projection axis into the so-called isocenter, and the whole X-ray system rotates around the isocenter. However, due to the system distortions caused by the gravity and mechanical influence, the isocenter could hardly be observed as a stable point [2]. Therefore, we define two isocenters, a frontal isocenter and a lateral isocenter, to explicitly model the biplane angiogram under that specific acquisition. When no system distortion is present, these two isocenters will coincide with each other. Otherwise, an isocenter offset is expected and this offset should be eliminated before the reconstruction of vascular centerlines.

Many sources of distortion might contribute to the isocenter offset, e.g., the gantry sag and the inaccurate reading of the acquisition angle. During many years of quality control on several X-ray systems at various hospitals, we found that gantry sag was the main reason leading to the
Assessment of Obstruction Length and Optimal Viewing Angle

Chapter 3

Shift of the isocenter. Due to the gravity and mechanical influence, gantry sag constantly happens during the image acquisition when the acquisition angle is adjusted. For a monoplane system, rotating the gantry to a different acquisition angle could cause a significant shift of more than 20 mm to its isocenter [7]. For a biplane system, either the frontal gantry or the lateral gantry could sag significantly under circumstances. The gantry sags from the two systems could add up, resulting in a significant isocenter offset.

Given the aforementioned facts, we ignore insignificant sources of distortions and assume that the uneven gantry sag between the frontal X-ray system and the lateral X-ray system is the only reason accounting for the isocenter offset. By this assumption, we define the imaging geometry as one X-ray system in fixed position with a shift equal to the amount of the isocenter offset in the other X-ray system. Figure 3-1 shows our 3D biplane model with an isocenter offset.

![Figure 3-1. 3D biplane model with an isocenter offset](image)

Due to the absence of pincushion distortion in modern X-ray systems with digital image intensifiers, each projection point should intersect with its corresponding epipolar line, when no system distortion is present. However, due to the presence of the isocenter offset, the projection of reference point A in the
frontal image intensifier, $A_F$, does not intersect with its corresponding epipolar line. The same holds for the reference point $B$. This ill-defined epipolar constraint can significantly jeopardize its usage in establishing the correspondence of the two projections for the 3D centerline reconstruction.

### 3.2.2 Approximation of the isocenter offset

In order to create a good correspondence between the frontal and lateral centerlines, i.e., to enforce the centerline points to correctly intersect with their corresponding epipolar lines, the isocenter offset should be calculated and eliminated. Due to the uncertainty of gantry sag, the real amount of isocenter offset varies for different acquisitions and is not reproducible. Our solution is to use one to three pairs of reference points, chosen from the anatomical landmarks visualized on both projections, e.g., the bifurcations, to approximate the isocenter offset.

![Figure 3-2. Correspondence before correcting for the isocenter offset](image1)

![Figure 3-3. Correspondence after correcting for the isocenter offset](image2)
The error of approximation is defined as the total distance from the reference points to their corresponding epipolar lines, e.g., the $A_F M_F$ and $B_F N_F$ in Figure 3-1. By using the aforementioned biplane geometry, the error can be formulated as an explicit function of the isocenter offset. By minimizing the error function, the approximation of the isocenter offset is obtained. An example of correspondence before and after eliminating the isocenter offset is given by Figure 3-2 and Figure 3-3, respectively. Clearly, the reliability of the epipolar constraint [5] was improved and good correspondence between the two projections was established after the elimination of the isocenter offset.

3.2.3 Centerline reconstruction

The vascular centerline is defined in this paper as the curve that passes through the center of the vessel lumen. The accuracy of the centerline reconstruction depends both on the 2D centerline extraction and on the 3D point reconstruction. In our approach, the lumen contours are automatically detected by a validated contour detection algorithm [8] after manually specifying the start and end positions of the segment of interest on the two projections. 2D centerlines are then extracted from the contours and used to reconstruct the 3D centerline.

The 3D point reconstruction algorithm requires the knowledge of correspondence between the frontal and lateral centerlines. This knowledge can be facilitated by using the epipolar constraint [5]. However, an ill-defined epipolar line due to the system distortions could cause significant error in the correspondence. Multiple intersections of the projected centerline and the epipolar line, as well as noise corruption in the centerline, could further deteriorate the correspondence. An example of the possible difficulties in creating correspondence by using the epipolar constraint is given by Figure 3-4.

Two possible types of errors might exist in creating the correspondence between the frontal and lateral centerlines:

1) The first error comes from the ill-defined epipolar lines due to the system distortion, mainly the isocenter offset. The correction of the isocenter offset in our 3D model will allow more accurate usage of the epipolar constraint in creating the correspondence, e.g., the corrected epipolar lines of the start and end points in Figure 3-4 correspond better with the vessel centerline than the original epipolar lines.

2) The second error comes from the noise-corrupt arterial centerlines, especially for those images with low contrast and a small perspective viewing angle, e.g., epipolar line $a$ in Figure 3-4, which could introduce quite cumbersome problems and affect the quality of correspondence.

To address the problems of using the epipolar constraint in difficult situations, a distance transform matrix is constructed based on the
distance from each projected centerline point to its corresponding epipolar line. A wave propagation algorithm [9] is then applied to search for a smooth corresponding path by which the propagation from the start position to the end position has the lowest cost. Based on the correspondence path, point reconstruction will be performed on based on the correspondence. We adopted the point reconstruction algorithm used by Dumay and Wahle [2, 5]. Each pair of corresponding points will generate two projection rays. The middle point of the shortest vector perpendicular to the two projection rays is used as the reconstruction point.

![Diagram of epipolar lines and corresponding points](image)

Figure 3-4. Possible difficulties in establishing the correspondence between the two centerlines by using the epipolar constraint.

### 3.3 Applications

#### 3.3.1 Obstruction length assessment

In coronary interventions, accurate assessment of obstruction length is of utmost importance for the selection of the appropriate stent size. The conventional approach to calculate obstruction length is to perform 2D QCA on the end-diastolic image frame [1, 10]. After defining the start and end positions of the obstruction, the pixel length is calculated and multiplied with the calibration factor to generate the obstruction length. Since the calibration factor only holds true for one particular plane perpendicular to the projection axis, e.g., the catheter plane or isocenter
plane, and this procedure assumes that the obstructed vessel segment lies in that particular plane; significant error due to the out-of-plane magnification [11] could exist when the assumption is not satisfied during the image acquisition. Besides, due to the 2D representation of the 3D vascular structures, 2D QCA has inherent limitations in assessing curved/bended segment length due to vessel foreshortening. The amount of foreshortening in 2D QCA varies with the shape of vessel and the experience of the operators in choosing the so-called optimal viewing angle during the image acquisition. A significant vessel foreshortening by performing 2D QCA on the operator-selected view in standard clinical acquisitions has been reported in early literatures [12-14].

Figure 3-5. Comparison of 3D QCA and 2D QCA in assessing obstruction length: Frontal image (top left panel) and lateral image (top right panel) are biplane data. Courtesy: Department of Cardiology, Leiden University Medical Center (LUMC), the Netherlands.

Figure 3-5 shows an example of comparing 3D QCA and 2D QCA in assessing obstruction length. The centerline and cross-sections of the segment of interest were reconstructed from biplane data (frontal image under 28.7 RAO and 0.3 Cranial, lateral image under 49.2 LAO and 0.2 Cranial) and the obstructed segment was automatically detected. The start and end positions of the obstruction in frontal image, lateral image, and the 3D view were synchronized. 2D QCA was performed on both frontal and lateral images by using isocenter calibration method. A significant error, caused by vessel foreshortening and out-of-plane magnification, was noticed from the 2D QCA assessments: The obstruction length in
- 3D reconstruction: 14.64 mm
- frontal image: 11.20 mm
- lateral image: 9.80 mm
length was measured as 11.20 mm in the frontal image and 9.80 mm in the lateral image, respectively, while the 3D obstruction length was 14.64 mm. The error in the frontal image comes predominantly from the out-of-plane magnification, since the obstructed vessel segment does not lie in the frontal isocenter plane, i.e., the plane perpendicular to the frontal projection axis and passing through the isocenter (the white intersection point of two yellow lines in Figure 3-5). Since the obstructed segment is also not close to the catheter plane, the out-of-plane magnification would still cause significant error, if the catheter calibration method instead of isocenter calibration method was used. The error of 2D QCA in the lateral image is caused by the combination of out-of-magnification and vessel foreshortening, which is more significant in this case.

3.3.2 Bifurcation optimal viewing angle assessment

Due to the increasing complexity of coronary interventions, in particular for bifurcation lesions, the identification of the optimal viewing angle is of increasing importance to the interventionalists to optimally deploy the stent. To stent certain types of bifurcation lesions, e.g., the one classified as 0,1,0 according to the Medina classification [15], a suboptimal viewing angle might not entitle the interventionalists to clearly visualize the ostium, possibly resulting in jailing of the sidebranch [16]. In case of stenting the ostium of a sidebranch, a good viewing angle could help the interventionalists to prevent stent protrusion into the main vessel or incomplete lesion coverage at the ostium of the sidebranch [17].

In routine clinical practice, the optimal viewing angle is subjectively selected by adjusting the rotation angle (LAO/RAO) and the angulation angle (Cranial/Caudal) of the X-ray system. This “trial-and-error” approach could significantly increase the amount of contrast medium administration and the radiation exposure to the patient and staff. In addition, due to the various experiences and preferences of the interventionalists, there is no guarantee that the chosen angle will optimize the visualization of the segment of interest. Therefore, a number of automated methods have been developed to identify the optimal viewing angle after the 3D reconstruction. Chen et al [18] defined the optimal viewing angle as the projection view having minimum foreshortening and overlap of a specific region in angiographic images. However, in case of a bifurcation with strongly curved main (parent) vessel, the viewing angle minimizing the foreshortening of the main vessel is not always the same view optimizing the visualization of the ostium of a sidebranch, e.g., the left main bifurcation [16]. Besides, the choice of a specific region for calculating the foreshortening and overlap is also subjective. Christiaens et al. [19] followed the method of determining
optimal viewing angle for a straight vessel by Dumay et al. [20] and defined the bifurcation optimal viewing angle as the angle perpendicular to the main direction of the bifurcation branches. Again, in a heavily curved main vessel, the optimal view calculated by this approach might not optimal for the ostium of the sidebranch, where the majority of restenosis occurred following T-stenting.

We have decided to take another approach and define a bifurcation main plane by fitting a plane using two centerlines within the bifurcation core, which starts from the proximal delimiter where the two centerlines start to split and ends at two distal delimiters where the bifurcation core ends and separates into two daughter branches, and by minimizing the distance from the carina to the plane. Figure 3-6 shows the definition of bifurcation main plane. The optimal viewing angle is determined by the direction perpendicular to the bifurcation main plane. By this viewing angle, the visualization of the ostium of the sidebranch is improved when a heavily curved main vessel is present.

Figure 3-6 shows a clinical example of a biplane acquisition. The frontal image was acquired under 35.8 RAO and 0.2 Caudal, while the lateral image was acquired under 53.4 LAO and 0.2 Caudal. The start and end positions of the bifurcation were indicated for the reconstruction. Figure 3-8 shows the visualization of the reconstructed bifurcation under the optimal viewing angle, being 52.0 LAO and 20.1 Caudal. Clearly, the bifurcation core and the sidebranch are well visualized, with minimum overlap under the optimal view. It is expected that this viewing angle will
enable the interventionalists to accurately see whether the stent has completely covered the ostium of the sidebranch and whether there is stent protrusion into the main vessel.

Figure 3-7. A biplane data: Frontal image (left); Lateral image (right). Courtesy, Dept of Cardiology, Leiden University Medical Center (LUMC), the Netherlands.

Figure 3-8. The reconstructed bifurcation under the optimal viewing angle, being 52.0 LAO and 20.1 Caudal.

3.4 Validations

3.4.1 Data acquisition protocols

Three wire phantoms with a number of markers were used in the validation study. At the Leiden University Medical Center, angiographic images were acquired using a Toshiba biplane X-ray system with a flat-panel image intensifier. The distance from the focal spot to the image
intensifier was set at 1100 mm. The first phantom was acquired with image size of 512×512 and intensifier size of 15 cm, while the other two phantoms were acquired with image size of 1024×1024 and intensifier size of 20 cm. All phantoms were acquired at multiple projections and images were stored in DICOM files. Figure 3-9 shows two of the wire phantoms used in the validation study. The thin cutting positions on the wires were used as markers.

![Figure 3-9. Wire phantoms used in the validation study.](image)

### 3.4.2 Segment length assessment

Twelve segments with length ranging from 16.5 mm to 39.0 mm were defined by the markers on the wire phantoms. The average length for these 12 segments is 24.15 mm. Each segment was reconstructed 4 to 5 times using different combinations of projections (with a difference of 30° to 120° in acquisition angles between the frontal and lateral projections) and its length was measured from each reconstruction, resulting in 52 QCA measurements. The accuracy of these measurements was assessed by comparing these with the known true length of the wire segments.

### 3.4.3 Bifurcation optimal viewing angle

In order to determine the ground truth of optimal viewing angle for each bifurcation, two orthogonal iron sticks were attached to each bifurcation, one stick on the main distal vessel and the other one on the sidebranch, with the first half parts of two iron sticks joining together as the optimal viewing vector. Figure 3-10 shows two projections of one wire phantom with the attached orthogonal iron sticks. The optimal viewing vector for each bifurcation was carefully adjusted to the best direction to view its related bifurcation. After that, the phantom was put back to the
same position on the table of the X-ray system as the previous acquisitions. For each bifurcation, the table was changed to the position where the bifurcation core was visualized in the middle of the projection image. Next, the rotation and angulation angles were adjusted until the optimal viewing vector was visualized as one point. The reading of the acquisition angles was used as the ground truth for that particular bifurcation. An example of the phantom under the optimal viewing angle for the lowest bifurcation (arrow in left image) and the middle bifurcation (arrow in right image) is given by Figure 3-10.

Figure 3-10. Determining the ground truth of optimal viewing angle by using the orthogonal iron sticks: Left image under 4 RAO and 40 Cranial; Right image under 44 LAO and 3 Cranial. The arrow indicates which bifurcation is optimally visualized.

A total of 6 bifurcations from three wire phantoms were used in the validation. Each bifurcation was reconstructed 8 times using different combinations of the projections (with a difference of 30º to 120º in acquisition angles between the frontal and lateral projections) and its optimal viewing angle was assessed from the reconstruction, resulting in 48 measurements.

3.5 Statistics

The correlation between 3D QCA segment length and the true wire segment length was calculated using Pearson’s correlation coefficient. The Bland-Altman plot was used to evaluate the difference between the 3D QCA assessment and the true length, while student t-test was performed to investigate the statistical significance of the difference.
The difference of optimal viewing angles between the 3D QCA assessment and the ground truth was evaluated by a scatter plot in terms of rotation angle and angulation angle. The mean difference of the optimal viewing angle was computed and considered to be an index to the accuracy of the QCA assessment, while the standard deviation of the difference was considered as an index of precision. Student t-test was performed to investigate the statistical significance of the difference.

All statistical analyses were carried out by using statistical software (SPSS, version 16.0; SPSS Inc; Chicago, IL, USA).

3.6 Results

The correlation of 3D QCA segment length and the true wire segment length is presented in Figure 3-11. The segment length assessed by 3D QCA correlated very well with the true wire segment length ($R^2 = 0.999$). Bland-Altman plot for the correlation is given in Figure 3-12. No trend for the difference as a function of the true length was found. The mean and standard deviation of the difference between QCA assessment and the true length were 0.04 mm and 0.25 mm, respectively. The difference was significant ($P < 0.01$), in other words, 3D QCA slightly overestimated the segment length by 0.04 mm for a segment with an average length of 24.15 mm.

![Figure 3-11. Correlation of 3D QCA with the true wire segment length.](image-url)
Chapter 3

Figure 3-12. Bland-Altman plot of 3D QCA and the true wire segment length.

Figure 3-13. Scatter plot for the difference of optimal view angle between 3D QCA assessment and the ground truth.

An optimal viewing angle consists of two parts: rotation angle and angulation angle. The scatter plot for the difference of optimal viewing angles assessed by 3D QCA and the ground truth in terms of these two parts is given by Figure 3-13. The shape of the scatter points represents the bifurcation case. No specific pattern was observed within any bifurcation case, indicating that the assessment was not sensitive to the
acquisition angles for the reconstruction. The descriptive statistics is given by table 1. The mean and standard deviation of the difference of rotation angles between QCA assessment and the ground truth was -1.5º and 3.6º, respectively. The difference was significant ($P < 0.01$). The mean and standard deviation of the difference of angulation angles between 3D QCA assessment and the ground truth were -0.2º and 2.4º, respectively. The difference was not significant ($P = 0.54$). In other words, 3D QCA slightly underestimated the optimal rotation angle by 1.5º.

| Table 1 The difference of optimal viewing angle between QCA assessment and the ground truth |
|---------------------------------|---------|---------|--------|--------|
|                                | Number of assessment | Minimum | Maximum | Mean   | Std. Deviation |
| Rotation (RAO)                 | 48       | -8.1º   | 5.6º    | -1.5º  | 3.6º       |
| Angulation (CAUD)              | 48       | -7.1º   | 5.8º    | -0.2º  | 2.4º       |

3.7 DISCUSSIONS

Over the past years, the development of coronary visualization and quantitative analysis systems has been motivated by the increasing need to better understand the true dimensions of vascular structures and by the on-line need for coronary interventions in catheterization laboratories. 3D QCA has received a lot of interest for the potential benefits of increasing the assessment capabilities for both diagnostic and interventional cardiology. It was thought that the 3D QCA could resolve a number of additional limitations of standard 2D analysis, such as elimination of foreshortening and out-of-plane magnification error [11]. In addition, the automatic identification of the optimal viewing angle might benefit the patients and staffs from less radiation exposure by reducing the trials in achieving the best “working view”.

Despite the fact that two simultaneously acquired images are available from biplane X-ray imaging systems, the development of a reliable and robust 3D QCA system is still not a trivial task. All current 3D QCA systems work best under conditions of the two X-ray systems rotating around the isocenter. However, the change of gantry geometry during the image acquisition might significantly shift the isocenter. In addition, the requirement of rotating two X-ray gantries around the same isocenter is a significant constraint to the operator in clinical routine. In other words, 3D QCA should also work accurately under non-isocentric conditions. In order to achieve this, the isocenter offset, i.e., the spatial displacement of the isocenters in the frontal and lateral systems, should be approximated and eliminated before the reconstruction. Ideally, a couple of reliable landmarks should be identified on both projections as reference points to determine the isocenter offset. On the other hand, the practical usage has
been hampered by the efforts in identifying many reliable landmarks, which turned out to be too time consuming or even impossible to identifying such reliable landmarks on the two projections. We have developed an approach by using only one to three pairs of reference points for the correction of the isocenter offset. The phantom validation by using only one or two markers as reference points to correct for the isocenter offset showed a high accuracy in the assessments of segment length and optimal viewing angle. In addition to the refinement of imaging geometry, we have also addressed the difficult problems in the centerline reconstruction when small perspective viewing angles and noise-corrupt arterial centerlines are present, which are expected to occur more frequently in routine clinical acquisitions. Although different acquisitions were used for the reconstruction (the acquisition angles for the frontal and lateral projections varies from 30° to 120°), the variations of the assessments for both segment length and optimal viewing angle were relatively small.

The delineation of vessel segment in 3D QCA could potentially increase the accuracy in stent selection. In current approaches, the selection of stent sizes mainly depends on the obstruction length assessed by visual estimation (eyeballing) or by 2D QCA. Conventionally, the calibration procedure, e.g., catheter calibration, should be performed at the first step of the assessment, which might as well introduce calibration variability. In addition, the foreshortening of the vessel of interest could cause significant underestimation of segment length [13, 21, 22], which could not be assessed or recognized directly from the 2D projections. The ad hoc solution of deploying additional stents when the first-select stent turns out to be of insufficient length could significantly increase the cost. Therefore, in some catheterization laboratories it becomes common for the interventionalists to consider the obstruction length a bit longer than the assessed result. As a result of that, the selection of stent might turn out to be longer than necessary, which could change unnecessarily the behavior of the arteries and associate a possible high risk of restenosis. On the other hand, the usage of automatic calibration in 3D QCA and the high accuracy of 3D QCA in segment length assessment could change the operator in decision making [12].

The ability to identifying the optimal viewing angle is another important feature of 3D QCA systems, especially for the on-line support of coronary interventions. Nevertheless, the optimal viewing angle has been interpreted differently: optimal viewing angle with minimal foreshortening and overlap [3], optimal viewing angle for the maximal exposure of lesion severity, or optimal viewing angle to optimally visualize the stent position in the bifurcation. These interpretations might generate different results
for certain bifurcations, e.g., the left main bifurcation with strongly curved left anterior descending artery. For the best interest of bifurcation related interventional procedures, we have decided to take the last interpretation and use the orthogonal view of the bifurcation main plane as the bifurcation optimal view, since we believe that this optimal view could benefit the interventionalists most in positioning the stent at the correct position and increase the angiographic success. An example case can be observed in T-Stenting: inappropriate view of the stent position might lead to incomplete lesion covering at the ostium of a side branch or stent protrusion into the main vessel [23]. Besides, this orthogonal view might as well expose the lesion severity at its maximum, due to the fact that atherosclerotic plaques occur preferably at the outer lateral wall of the bifurcation, i.e., the site opposite to the carina, where flow is more turbulent and endothelial shear stress is lower.

Despite high accuracy and robustness have been achieved by our 3D QCA system, the practical usage of the system has been hampered by the fact that biplane X-ray angiograms are hardly used in routine interventional cardiology. However, combing with the ECG-gated technique, our approach can be extended with a solution for monoplane X-ray systems. The introduction of isocenter offset correction could also be expected to eliminate the shift of heart caused by the patient respiration when changing the gantry from the first projection to the second projection. Future work is directed at performing extensive clinical validations for monoplane X-ray systems.

3.8 Conclusions
A novel 3D QCA system based on X-ray angiograms has been achieved by introducing a highly reproducible vessel centerline reconstruction. The validation study by using wire phantoms showed a high degree of accuracy and precision in the assessments of segment length and optimal viewing angle.

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