Comparison of 3D reconstruction methods based on different cardiovascular imaging: a study of multimodality reconstruction method

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Abstract— **Coronary arterial imaging and the assessment of the severity of arterial stenoses can be achieved with several modalities classified mainly according to their invasive or noninvasive nature. These modalities can be further utilized for the 3-dimensional (3D) reconstruction of the arterial geometry. This study aims to determine the prediction performance of atherosclerotic disease progression using reconstructed arteries from three reconstruction methodologies: Quantitative Coronary Analysis (QCA), Virtual Histology Intravascular Ultrasound (VH)-IVUS-Angiography fusion method and Coronary Computed Tomography Angiography (CCTA). The accuracy of the reconstruction methods is assessed using several metrics such as Minimum lumen diameter (MLD), Reference vessel diameter (RVD), Lesion length (LL), Diameter stenosis (DS%) and the Mean wall shear stress (WSS). Five patients in a retrospective study who underwent X-ray angiography, VH-IVUS and CCTA are used for the method evaluation.**

I. Introduction

In western societies coronary artery disease (CAD) and especially atherosclerosis is the leading cause of death [1]. Atherosclerosis is an inflammatory disease of the coronary, carotid and other large arteries, which is caused by high plasma concentrations of cholesterol, in particular low-density lipoprotein (LDL) and other lipid-bearing materials in the arterial wall [1]. It starts with lipid oxidation, which can provoke chronic inflammation resulting to plaque growth. Atherosclerotic plaques are created in the intima of the arteries and gradually expand in the arterial wall. Several risk factors (i.e. genetic, biological and environmental) contribute to the occurrence and progression of atherosclerosis. Atherosclerosis tends to localize in regions with curvature and branches. Blood flow exerts shear stress (WSS) on the lumen wall. WSS is an important biomechanical parameter in the progression of atherosclerosis. In addition, the location of plaque rupture is also related to WSS distribution. Areas of low WSS are generally prone to plaque development [2-3].

For these purposes, advances in signal and image processing have allowed the development of 3-dimensional (3D) reconstruction of the coronary vasculature and the *in vivo* evaluation of WSS. Several imaging modalities, invasive or noninvasive, have been developed for the reconstruction of the coronary anatomy, Invasive Coronary Angiography (ICA), Virtual-Histology Intravascular Ultrasound (VH-IVUS), Coronary Computed Tomography Angiography (CCTA), are some of the most well-known and used imaging modalities.

ICA provides an accurate visualization of the coronary anatomy and the degree of luminal stenosis. The limitations of this imaging modality are the vessel overlap, vessel foreshortening and variable magnification. It also fails to deliver any information about the arterial wall or the presence of atherosclerotic plaques. CCTA is a noninvasive imaging modality, which can provide data on the arterial lumen, the arterial wall and can also detect stenoses, as well as, the atheromatic plaque location. This modality fails to deliver accurate information about the coronary vasculature when highly calcified plaques are present, due to the "blooming effect". The gold standard for acquiring information regarding the arterial wall and the plaque composition is Intravascular Ultrasound (IVUS). Moreover, IVUS provides a 2D view of the arterial lumen and a modest view of the atherosclerotic plaque. However, it does not provide the 3D information about the geometry of the lumen, the actual location of each frame and the low spatial resolution, which may also include visual artifacts. One of the most widely accepted reconstruction methods is based on the fusion of ICA and IVUS imaging. This method provides a detailed representation of the coronary artery since ICA provides information on the geometry of the vessel and IVUS allows the accurate assessment of the luminal and vessel wall morphology.

The development of these imaging modalities has allowed the accurate 3D reconstruction of the coronary vasculature. The advances in Computational Fluid Dynamics (CFD) and the application of CFD on the 3D models that derive from the aforementioned method has constituted them a useful tool in everyday clinical practice [4, 6-11].

The purpose of this study is to evaluate the accuracy of each reconstruction method using several metrics such as Minimum Lumen Diameter (MLD), Reference Vessel

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Diameter (RVD), Lesion Length (LL), Diameter Stenosis (DS) and finally the Mean Wall Shear Stress (WSS).

II. Materials and Methods

A. Dataset

Five patients, (2 females and 3 males, mean age: 59±3 years) were enrolled in a retrospective study from January 2007 and September 2009 (baseline and 24-month follow up) and were recruited for ICA (IntegrisAllurs Flat Detector), VH-IVUS (Visions® PV .018 Catheter, Volcano Corp.) and CCTA (Toshiba Aquilion 64-slice detector) exams at the InCor hospital of Sao Paolo, Brazil. Five coronary arteries, two Right Coronary Artery (RCA) and three Left Anterior Descending (LAD) are used in this study.

B. 3D Reconstruction

Anatomical landmarks (i.e. the origin of side branches) were used to identify and reconstruct the same parts of the coronary arteries for each case.

B.1) Quantitative Coronary Analysis

Quantitative Coronary Analysis (QCA) is based on coronary angiography and usually considers only one or more coronary segments. The first step in order to perform a QCA analysis is to acquire high-quality angiographic images focused on the target coronary artery segment of choice [3].

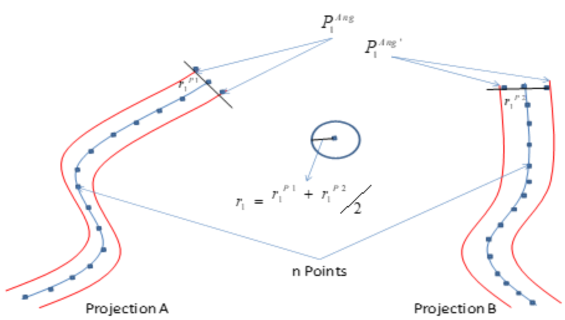

Figure 1. 3D reconstruction procedure with our 3D-QCA method [5].

Using our in-house developed algorithm, based on coronary angiography we reconstructed the arterial segments. For each view, an end-diastolic frame from each projection is used. A minimum angle difference of 30°is required. Furthermore, the user manually segment the luminal borders of the region of interest (ROI) using specific landmarks in the two projections. Then the automatic edge detection algorithm detects the centerline by choosing $n$equidistant points for each centerline. The perpendicular line in each of n points is calculated and defined. In each projection the perpendicular lines intersect the silhouettes of the vessel projections in two points P_1^{Ang} and $P_1^{Ang'}$ having a distance r_1^{P1} and r_1^{P2} from the first and the second silhouette, respectively. For each of n points, n circular contours are computed with a radius that is calculated by:

$$r_1 = \frac{r_1^{P1} + r_1^{P2}}{2} \tag{1}$$

Finally a 3D path is reconstructed and the circular contours are stacked perpendicularly on the 3D centerline, thus generating 3D arterial model, after the image calibration that is performed using the digital pixel size. The whole reconstruction process is depicted schematically in Fig.1.

B.2) VH-IVUS-Angiography fusion

This approach requires a VH-IVUS pullback sequence and two end-diastolic angiographic views (≥30° apart), where is avoided foreshortening or underestimation of stenoses severity, in order to reconstruct the vessel geometry. Arterial segments were reconstructed following our validated method [3, 7, 11-12]. First, the VH-IVUS frames were binarized using an appropriate MATLAB algorithm [3] and the luminal and outer wall borders were detected automatically. The luminal borders of each segment were portrayed by two angiographic projections and the respective 2D centerlines were automatically extracted. Then the aforementioned centerlines were fused to create the final 3D centerline. The generated 3D centerline was used to stack the VH-IVUS segmented frames perpendicularly, thus displaying the actual 3D arterial model. Finally, using the annotated branches from the VH-IVUS images, the corresponding absolute orientation of the 3D model was performed and the final 3D accurate mode for the arterial segment was created (Fig. 2).

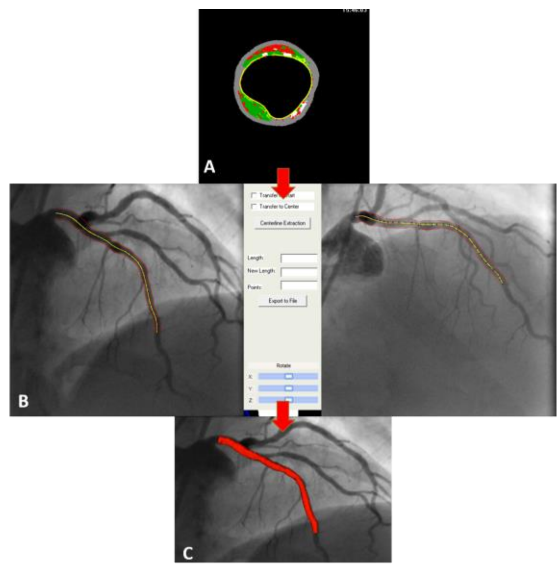

Figure 2. Flow chart representing the reconstruction steps for the hybrid 3D reconstruction method. A) Lumen annotation in the corresponding VH-IVUS frame. B) 3D centerline extraction process. C) Final 3D model of the artery, back-projected on the corresponding angiography frame [12].

B.3) Coronary Computed Tomography Angiography

CCTA is another validated method for the diagnostic investigation of coronary artery disease (CAD) and the prediction of future events. CCTA image reconstruction uses filtered backed projection (FBP). We utilized our 3D reconstruction method using the following steps [13]:

i. We use the Frangi Vesselness Filter on the preprocessed CCTA images for the automated definition of the region of interest (ROI).
ii. The blooming effect created from the highly calcified (Ca) plaques is removed.
iii. The 3D centerline is extracted.

iv. The lumen, outer wall and the atherosclerotic plaques are extracted based on the Hounsfield Units (HU) scale.
v. A level set algorithm is applied on plaque segmentation considering calcified objects of significant size.
vi. Finally, 3D reconstructed models for the lumen, outer wall and calcified plaques are generated.

C.) Modeling of Blood Flow

In order to evaluate the accuracy of each reconstruction method we performed the same blood flow simulation for each 3D reconstruction. The flow simulation parameters are described below.

C.1) Rigid Wall Assumption

We assume that blood flow is laminar and incompressible while blood behaves as a Newtonian fluid, with dynamic viscosity 0.0035 (Pa·s) and density 1050 kg/m^3. The generated flow was considered laminar and incompressible. The Reynolds number ranged from 508-730. The Navier-Stokes and the continuity equations were used to model blood flow:

$$\rho\frac{\partial \mathbf{v}}{\partial t}+\rho(\mathbf{v}\bullet\nabla)\mathbf{v}-\nabla\bullet\boldsymbol{\tau}=0, \quad (2)$$

$$\nabla\bullet(\rho\mathbf{v})=0, \quad (3)$$

Where **v** is the blood velocity vector and τ is the stress tensor, which is defined as:

$$\boldsymbol{\tau}=-p\delta_{ij}+2\mu\varepsilon_{ij}, \quad (4)$$

where δ_{ij} is the Kronecker delta, μ is the blood dynamic viscosity, p is the blood pressure and ε_{ij} is the strain tensor calculated as:

$$\varepsilon_{ij}=\frac{1}{2}\left(\nabla\mathbf{v}+\nabla\mathbf{v}^T\right). \quad (5)$$

C.2) Boundary Conditions

At the inlet, a flow velocity of 0.15 m/s was used in all cases. At the outlet, a zero pressure boundary condition was used, whereas for the wall, a no-slip and no-penetration boundary condition applies.

C.3) Mesh

The final 3D models were discretized into tetrahedral elements with an element size ranging from 0.09-0.1 mm. The element size was determined after a mesh sensitivity analysis.

III. RESULTS

Our primary goal in this study was to examine and investigate the accuracy of each imaging modality and the comparison of modalities. This was done by performing quantitative analysis in each modality by calculating the MLD, RVD, LL, DS% in all 3D models [5].

- RVD (mm) is defined as the average diameter of healthy coronary artery.
- MLD (mm) is defined as the smallest lumen diameter in the segment of interest.
- DS (%) is defined as (RVD-MLD)/RVD.
- LL (mm) is the length of the stenotic segment calculated from the 2 points between the angiographically normal segment and the disease segment.

Furthermore, in order to investigate the effect of reconstruction method on CFD simulation we calculate the Mean WSS (Pa) for each case (TABLE I).

TABLE I. CALCULATED RVD (mm), MLD (mm), DS (%), LL (mm) AND MEAN WSS (Pa) FOR ALL CASES.

	BASELINE	*FOLLOW*	*TOTAL*
QCA			
RVD (mm)	3.81 ±0.60	3.75±1.30	3.78 ±0.96
MLD (mm)	2.04 ±0.58	3.02 ± 0.74	2.53 ±0.83
DS (%)	46.5 ± 12.2	28.6 ±9.47	37.5 ±13.9
LL (mm)	7.30 ±9.08	3.14±1.65	5.22 ±6.54
Mean WSS (Pa)	3.20 ±1.34	3.27 ±1.09	3.23±1.15
VH-IVUS			
RVD (mm)	3.56 ± 0.79	3.14±0.70	3.35 ± 0.73
MLD (mm)	1.69 ± 0.73	2.65 ± 0.76	2.17 ± 0.86
DS (%)	53.0 ± 12.9	25.2± 10.6	39.1 ±18.40
LL (mm)	5.08 ± 3.80	2.62 ± 1.55	3.85 ± 3.03
Mean WSS (Pa)	3.60± 1.62	3.71 ± 1.37	3.65 ± 1.41
CCTA			
RVD (mm)	3.36 ± 0.76		
MLD (mm)	2.17 ± 0.90		
DS (%)	39.6 ± 18.5		
LL (mm)	5.70 ± 8.01		
Mean WSS (Pa)	3.46 ± 1.44		

Association between metrics estimated by VH-IVUS-Angiography fusion, QCA, CCTA – based models.

- Reference Vessel and Minimum Lumen Diameter

The mean value of RVD (mm) measured by QCA, VH-IVUS –ICA fusion and CCTA in baseline (BL) was (3.81 ± 0.60), (3.56 ± 0.79), (3.63 ± 0.76), respectively, and in follow-up for the first two image modalities (FU) (3.75 ± 1.30), (3.14± 0.70). No significant difference was observed between three image modalities. The RVD measured by the fusion method was correlated with that measured by CCTA (r=0.92, P=0.029) higher than the measured one QCA (r=0.56, P=0.326). On the other hand the correlation of MLD (mm) was stronger between VH-IVUS-ICA fusion and CCTA based reconstructions models (r=0.95, P=0.012) than the fusion method and QCA based models (r=0.81, P=0.093).

- Degree of Stenoses DS(%) and Lesion Length

The mean difference for DS (%) between QCA and the VH-IVUS –ICA fusion method (r=0.83, P=0.085) was smaller than the fusion method and CCTA (r=0.69, P=0.029). As well as, the mean difference for LL (mm) was higher between the VH-IVUS –ICA fusion and QCA method reconstructed models (r=0.92, P=0.026) than the fusion method and CCTA (r=0.90, P=0.036).

- Mean Wall Shear Stress Analysis

No significant difference was observed between the three methods for the Mean WSS value (Fig. 3) but there was a stronger and significant correlation between VH-IVUS-ICA fusion and QCA reconstruction method(r=0.99, P=0.002) than the correlation between VH-IVUS-ICA fusion and CCTA method (r=0.98, P=0.007) (Fig. 4).

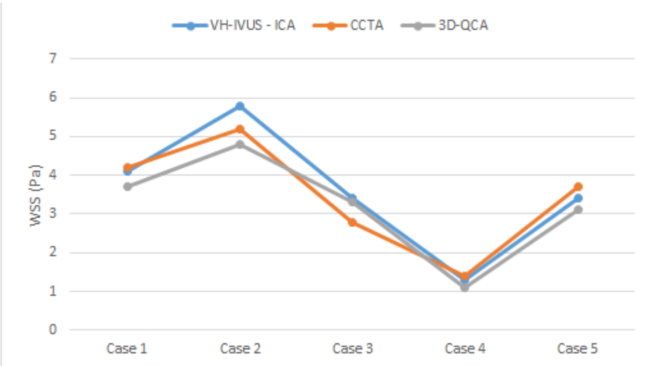

Figure 3. Relation of Mean WSS for each reconstruction method.

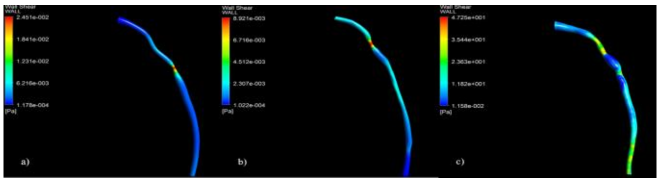

Figure 4. 3D models of Mean WSS for each reconstruction method: a) QCA method, b) VH-Angio fusion method and c) CCTA method.

IV. DISCUSSION

In this work we examined the performance of each imaging modality with the contribution of various metrics and we compared those methods in the same coronary segments in order to achieve it.

In this study, it has been shown that the QCA overestimates RVD in comparison with the other two modalities especially in diffusely diseased vessels. The measured RVD and obtained by the fusion method revealed a higher correlation with the one obtained by CCTA than obtained by QCA. Moreover, the measured MLD had a higher correlation between QCA and the fusion method. Furthermore, for the mean value of DS (%) we observed a significant difference between the VH-IVUS-ICA fusion and QCA method. However, for the measured LL (mm), we observed that we had a good correlation between the three methods.

Finally, we found a significant correlation between the Mean WSS value estimated in QCA, the fusion method and CCTA based models. Regarding the measured Mean WSS, the QCA method exhibited the lowest values, mainly because the 3D models were smoothest than the other two modalities.

The results of this study have several clinical implications and particularly from the point of view of interventional procedures. Therefore, further research is needed to examine the performance, maybe in a larger dataset, of the prediction for these three image modalities.

V. LIMITATIONS

A limitation of the present analysis is the fact that QCA, VH-IVUS fusion Angiography and CCTA models did not include the side branches of the reconstructed geometry, which can possibly affect the Mean WSS. The vessel angulations and tortuosity could influence the results of length measurements. In addition the number of patients and segments included was low and there was no exams for the follow-up for the CCTA method to allow to investigate the best accuracy of the prediction of each imaging modality.

VI. CONCLUSIONS

Our study demonstrated the efficiency of three image modalities, QCA, VH-IVUS-Angiography fusion method and CCTA in the assessment of the hemodynamic severity of a coronary stenoses. However, several patients must be added in the dataset in order to be sure about the efficiency of better prediction.

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