A comparison of three multimodality coronary 3D reconstruction methods

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***Abstract*—The assessment of the severity of arterial stenoses is of utmost importance in clinical practice. Several image modalities invasive and non-invasive are nowadays available and can be utilized for the 3-dimensional (3D) reconstruction of the arterial geometry. Following our previous study, the present study was conducted to further strengthen the evaluation of three reconstruction methodologies, namely: (i) the Quantitative Coronary Analysis (QCA), (ii) the Virtual Histology Intravascular Ultrasound VH-IVUS-Angiography hybrid method and (iii) the Coronary Computed Tomography Angiography (CCTA). Data from 13 patients were employed to perform a quantitative analysis using specific metrics, such as, the Mean Wall Shear Stress (mWSS), the Minimum Lumen diameter (MLD), the Reference Vessel Diameter (RVD), the Degree of stenosis (DS%), and the Lesion length (LL). A high correlation was observed for the mWSS metric between the three reconstruction methods, especially between the QCA and CCTA (r=0.974, P<0.001).**

Keywords: Coronary atherosclerosis, 3D reconstruction, Mean Wall Shear Stress

I. INTRODUCTION

Although in the last decades enormous efforts have been made to minimize the treatment of the cardiovascular disease (CAD), it still remains one of the primary causes of death in most countries worldwide. The most prevalent of the cardiovascular diseases is considered to be atherosclerosis. It is characterized by chronic inflammation, fibroproliferation of the large and medium sized arteries, affecting mainly the coronary arteries, the arteries of lower limbs, the carotid arteries and the internal aorta [1].

Atherosclerosis has a focal and eccentric character and each lesion evolves in an independent manner, despite the fact that the vasculature system is exposed to systemic risk factors. The major factor of the atherosclerosis is the high plasma concentration of cholesterol, in particular low-density lipoprotein (LDL), and other lipid-bearing materials in the arterial wall [2]. A lipid oxidation procedure starts which can provoke chronic inflammation resulting to plaque growth. The vascular endothelium and the luminal surfaces of the blood vessel is in a unique position to expose constantly to hemodynamic forces [3]. Through that study they proved that the low shear stress (SS) affects the local supply and removal rates.

In the last thirty years, a series of investigations have validated the major role of low SS in the progression of atherosclerotic lesions and plaques. In the early 1970s another hypothesis was advanced by Fry et al. [4], who implicated that high SS is another factor via endothelial damage, promotion of platelet deposition and plaque rupture. Through this explanatory mechanism for the association between birth of atherosclerosis and hemodynamic factors, we come to the conclusion that hemodynamic forces play a major role since they create a unique environment for the formation of atherosclerotic lesions at specific regions of the arterial tree.

A great effort was made in the last years in order to address this major problem. The augmented treatment options have created a need for better and more detailed imaging of coronary artery pathology. In addition, with the simultaneous development in medical imaging, a multitude of imaging modalities exist for the evaluation of the extent and severity of the CAD.

Advances in image processing have allowed the reconstruction of 3D models of the coronary anatomy and the detection of the atherosclerotic plaques via non-invasive image modalities like Computed Coronary Tomography Angiography (CCTA) and Magnetic Resonance Imaging (MRI). Nowadays CCTA is a useful modality for the detection of stenotic area because of its ability to provide data for the arterial lumen and the wall and for the atheromatic plaque location. On the other hand, it fails to provide information about the plaque burden, especially in small and stented coronaries, as well as, when high calcified plaques appear, due to the “blooming effect”. In addition, MRI does not provide the appropriate accuracy in the coronary pathology since its poor resolution limits the coronary visualization.

For this reason, the use of invasive imaging modalities is necessary to address the limitations of the non-invasive

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modalities. The most well-known invasive imaging modalities are the Invasive Coronary Angiography (ICA), the Intravascular Ultrasound (IVUS), as well as, the Virtual Histology Intravascular Ultrasound (VH-IVUS). ICA continues to constitute the most popular image modality to estimate the degree and the severity of the luminal stenosis since it allows the holistic visualization of the coronary anatomy. The limitations of this image modality are: (i) the lack of information about the plaque composition and burden, and (ii) the vessel overlap, foreshortening and variable magnification. These drawbacks of ICA were overcomed by IVUS.

IVUS has the ability to provide high-resolution cross-sectional images that portray: (i) the 2D view of the arterial morphology (lumen and wall), and (ii) a modest view of the plaque composition of the atherosclerotic plaque. Therefore, the IVUS is considered the gold standard for the scientific community. However, its low spatial resolution leads to the creation of artifacts and it is unable to provide the 3D information of the lumen and the actual location of each frame.

The current advancements in image processing aim to overcome all these limitations through the combination of the information that is provided by two different image modalities. In fact, data fusion allows a more thorough representation of the vessel anatomy via hybrid models. One of the most well-known fusion methods is based on the fusion of IVUS and ICA. The reconstructed models of this method provide a detailed representation of the coronary artery since ICA provides information regarding the geometry of the vessel and IVUS allows the accurate assessment of the luminal and vessel wall morphology.

Even though the aforementioned image modalities made their appearence in the last few years, they have a recognized role. Their rapid progress has enabled the development of the Computational Fluid Dynamics (CFD) models which allow the blood flow in realistic geometries, sometimes including deformable walls. The application of CFD on the 3D models has constituted them a useful tool in the clinical arena.

In this work we aim to extent a previous study [5]. More specifically, we have performed a quantitative analysis by calculating specific metrics, such as, the: (i) Mean Wall Shear Stress (mWSS), (ii) Minimum Lumen Diameter (MLD), (iii) Reference Vessel Diameter (RVD), (iv) Degree of Stenosis (DS%), and (v) Lesion Length (LL).

II. Materials And Methods

A. Patient selection

In a retrospective study, thirteen patients (6 females and 7 males with mean age: 60±3 years) were enrolled from January 2007 (baseline) to September 2009 (24-month follow up). All patients underwent ICA (IntegrisAllurs Flat Detector), VH-IVUS (Visions® PV .018 Catheter, Volcano Corp.) and CCTA (Toshiba Aquilion 64-slice detector) examination at the InCor hospital of Sao Paolo, Brazil. For the validation of this study thirteen coronary arteries were investigated, consisting of 4 Right Coronary Arteries (RCA), 7 Left Anterior Descending Arteries (LAD), and 2 Left Circumflex Arteries (LCX).

B. 3D Reconstruction Methods

3D models were derived from three different image modalities and were further employed in order to reconstruct the same parts of the coronary arteries. Anatomical landmarks were finally recognized for each case.

B.1) Quantitative Coronary Analysis

In this method, the arterial segments were reconstructed using a novel method that was developed based on coronary angiography. We utilized our reconstruction method in two steps. First, the user manually segments the target coronary segment of choice in two angiographic views with minimum angle difference 30°, and then the automatic edge detection algorithm detects the centerline by choosing n-equidistant points [6]. Then, for each centerline, the perpendicular line in each of the n points is calculated.

In each projection, the perpendicular lines intersect the silhouettes of the vessel projection in two points $\left(P_1{}^{Ang}, P_2{}^{Ang}\right)$, having a distance $(r_1{}^{P_1})$ from the first silhouette and $(r_1{}^{P_2})$ from the second one. Then, the n circular contours are computed with a radius calculated as:

$$r_1 = \frac{r_1{}^{P_1} + r_1{}^{P_2}}{2}. \quad (1)$$

Finally, the 3D path is reconstructed and the lumen contours are placed perpendicularly on the 3D centerline after the image calibration, generating the 3D arterial model.

B.2) VH-IVUS -Angiography Hybrid Method

All arterial segments were reconstructed following our validated method [6-10]. This method requires a VH-IVUS pullback and two end-diastolic angiographic views. The VH-IVUS frames were automatically segmented for each case using the algorithm described in [6]. Then the 2D centerline of each segment was extracted and the segmented luminal borders were fused to create the final 3D centerlines. This centerline was used to place the VH-IVUS images perpendicularly, thus generating the actual 3D arterial model. Finally, the 3D accurate model of the arterial segment was created by employing the corresponding absolute orientation of the 3D model via the annotated branches of the VH-IVUS frames.

B.3) Coronary Computed Tomography Angiography

CCTA is an innovative methodology for the diagnosis of CAD and the prediction or future events through the 3D reconstruction of the whole arterial tree. This method is based on filtered back projection (FBP) and includes the following steps [11]: (i) the selection of the region of interest (ROI) using a Frangi Vesselness filter on the preprocessed CCTA images, (ii) the removal of the “blooming effect” from the lumen and outer wall, as well as, for the highly calcified (Ca) and non-calcified (NCa) plaques, where the extraction of the aforementioned characteristics is based on the Hounsfield Units (HU) scale, (iii) the plaque segmentation which is performed through an algorithm that is based on the level set approach which accounts for Ca objects of significant size, and (iv) in the final step the segmented surfaces are connected to construct the 3D models for the lumen, outer wall and plaques.

C) Modeling of Blood Flow

The obtained geometries were used in the CFD calculation to evaluate the accuracy of each reconstruction method.

C.1) Boundary Conditions-Mesh

Blood flow was assumed to be laminar and incompressible while blood was treated as a homogeneous and Newtonian fluid with dynamic viscosity 0.0035 ($Pa \cdot s$) and density 1050 kg/m^3. A steady flow with a uniform profile specified at the inlet with flow velocity 0.15 m/s is assumed. For the arterial wall no-slip and no penetration boundary condition were applied while zero pressure was used at the outlet. The final 3D models were discretized into tetrahedral elements with size 0.09-0.1 mm which was determined using a mesh sensitivity analysis, and the WSS was estimated at the lumen surfaces. The CFD software based on finite element (FE) method for the solution of Navier-Stokes and the continuity equations were used to model blood flow.

III. Results

The aim of this study was to carry out an extensive investigation of the accuracy of each image modality and a comparison between them. In each modality, we use the RVD, MLD, mWSS, LL and DS% comparison measures. The results for each case are given in Table I.

TABLE I. Calculated RVD (mm), MLD (mm), DS (%), LL (mm) and Mean WSS (Pa).

	BASELINE	***FOLLOW-UP***	***TOTAL***
QCA			
RVD (mm)	3.09 ± 0.83	3.19 ± 0.96	3.14 ± 0.89
MLD (mm)	1.91 ± 0.49	2.48 ± 0.70	2.19 ± 0.59
DS (%)	39.7 ± 14.4	25.5 ± 10.8	32.6 ± 12.6
LL (mm)	6.40 ± 7.08	2.34 ± 2.60	4.37 ± 4.84
Mean WSS (Pa)	2.49 ± 1.10	3.20 ± 0.88	2.85 ± 0.99
VH-IVUS			
RVD (mm)	2.99 ± 0.81	2.94 ± 0.56	2.96 ± 0.68
MLD (mm)	1.67 ± 0.54	2.37 ± 0.63	2.02 ± 0.58
DS (%)	46.6 ± 13.5	25.7 ± 9.31	36.2 ± 11.4
LL (mm)	3.10 ± 2.10	1.61 ± 4.55	2.36 ± 3.33
Mean WSS (Pa)	2.50 ± 1.41	3.26 ± 1.03	2.88 ± 1.22
CCTA			
RVD (mm)	3.00 ± 0.82		
MLD (mm)	1.93 ± 0.68		
DS (%)	35.2 ± 15.4		
LL (mm)	3.80 ± 5.01		
Mean WSS (Pa)	2.58 ± 1.23		

A. *Mean Wall shear stress analysis*

In order to investigate the effect of reconstruction method on CFD simulation we calculate the mWSS (Pa). For this measure, no significant differences were observed for the various image modalities used in the 3D reconstruction (Fig. 1). At the baseline, where the comparison of the 3 methods was possible, we observe a strong correlation between the QCA method and the CCTA method ($r = 0.974, P < 0.001$) than the rest of the correlations that were derived by the combination of the other two methods. In the 24-month follow-up, after the investigation of the comparison of QCA and VH-IVUS-ICA fusion method the correlation was significant ($r = 0.764, P < 0.001$) (Fig. 2).

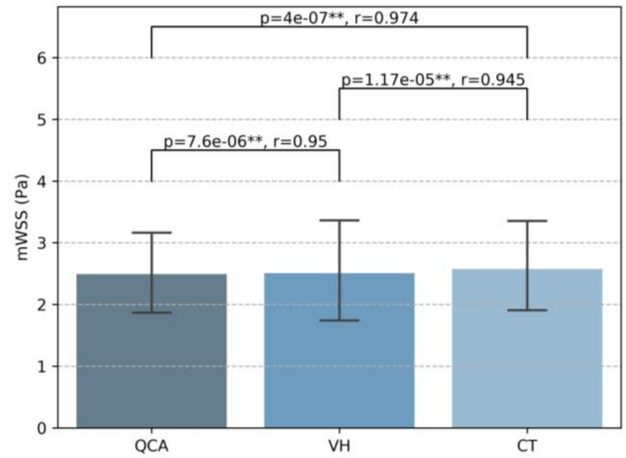

Figure 1. Correlation plots of Mean WSS for each reconstruction method at baseline.

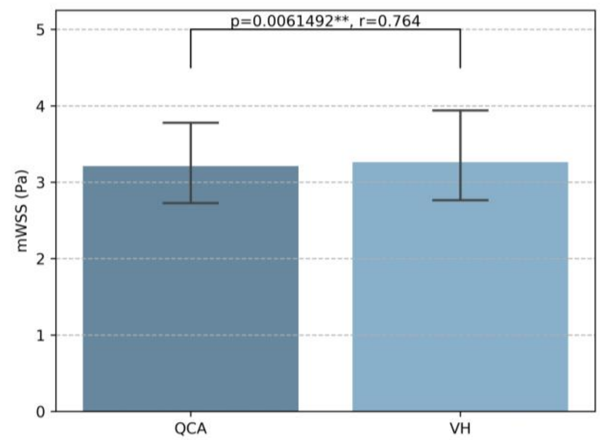

Figure 2. Correlation plots of Mean WSS for each reconstruction method at 24-month follow up.

B. *Minimum Lumen and Reference Vessel Diameter*

MLD was defined as the smallest lumen diameter in the segment. For this parameter we have a higher correlation at the baseline between the QCA reconstruction method and the VH-IVUS-ICA hybrid method ($r = 0.928, P < 0.001$) than the other possible combinations: (i) the QCA-CCTA ($r = 0.772, P < 0.001$), and (ii) the VH-IVUS-ICA-CCTA ($r = 0.829, P < 0.001$), respectively, and at the follow up for the first two methods ($r = 0.247, P = 0.46$). On the other hand, for the RVD factor, a significant correlation was observed for the VH-IVUS-ICA fusion method and the CCTA ($r = 0.968$, $P < 0.001$) at the baseline. Finally, the correlation for the follow up between the QCA and the VH-IVUS-ICA was ($r = 0.114, P = 0.74$).

C. *Degree of stenosis and Lesion Length*

The mean difference of DS% at baseline between the QCA and the CCTA method ($r = 0.937, P < 0.001$) was higher than the other two comparisons. In the follow up, the correlation for the QCA and the Fusion method was weaker

$(r = 0.571, P = 0.06)$. Finally, for the LL, the higher correlation was found between the Hybrid method and the QCA method $(r = 0.91,\ P < 0.001)$.

IV. Discussion

This study presents a comparison in human coronary arteries of the accuracy of three different reconstruction methods, namely the QCA, the VH-IVUS-ICA fusion, and the CCTA. The comparison was carried out in the same coronary segments by employing various metrics.

As we know hemodynamic forces play a major role in the progression of the atherosclerosis. In the last years many investigations concluded that the WSS constitutes a prediction factor for this disease. In this study, we found a significant correlation for the Mean WSS between the three methods under investigation, where the strongest one was observed between the QCA method and the CCTA method ($r = 0.974, P < 0.001$). Furthermore, the QCA method was found to exhibit the lowest values due to the smoothness of the reconstructed walls against the other two methods.

Moreover, in this study we discovered that the measured MLD had a higher correlation between the QCA and the CCTA, although in our previous study, with a smaller dataset, we observed that the higher correlation was between the QCA and the Fusion method. In the same scale, the change in the best correlation has also evolved for the DS% with the best correlation to be observed between the QCA and the CCTA methods. However, the higher correlation for the RVD measurements remains stable and was observed between the VH-IVUS-ICA and CCTA methods. For the factor of LL, a significant correlation between the QCA and the Fusion methods was observed, although in this case we had a good correlation between the three methods.

V. Limitations

Two main limitations remain which need to be considered during the interpretation of the present study. The first one was the lack of large CCTA follow up dataset. In order to deal with this, we will try to increase the number of patients in order to verify this conclusion. Another problem of this study was the lack of the side branches that was present in the reconstructed geometry, which has an effect both on the Mean WSS and on the length measurements.

VI. Conclusion

In the current study, we discovered significant correlations between two metrics (RVD, LL) by comparing three image modalities across 13 patients. However, several efforts must be done in order to improve the performance of the three reconstruction methods towards the effective assessment of the hemodynamic severity of coronary stenosis.

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