In-vivo accuracy of geometrically correct three-dimensional reconstruction of human coronary arteries: is it influenced by certain parameters?

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Objective **The geometrically correct three-dimensional reconstruction of human coronary arteries by integrating intravascular ultrasound (IVUS) and biplane angiography constitutes a promising imaging method for coronaries with broad clinical potential. The determinants of the accuracy of the method, however, have not been investigated before.**

Methods **In total, 17 arterial segments (right coronary artery, $n=7$; left anterior descending, $n=4$; left circumflex, $n=6$) derived from nine patients were three-dimensionally reconstructed by applying three-dimensional intravascular ultrasound. The degree of matching between the reconstructed lumen back-projected onto each angiographic plane and the actual lumen in each plane was used as a measure of method's accuracy. The investigated factors that could potentially affect the reliability of the method included the type of the artery (left anterior descending, left circumflex, right coronary artery) and several geometrical and morphological characteristics of the reconstructed arteries.**

Results **The correlation between the back-projected reconstructed lumens and the actual angiographic ones was found to be high ($r=0.78$, $P<0.001$). Neither the category of the reconstructed arteries nor their particular geometrical and morphological characteristics influenced the accuracy of the reconstruction method significantly. Nonetheless, the method exhibited slightly less accuracy in the reconstruction of right coronary arteries, an observation that could be attributed to the more intense pulsatile motion that this artery experiences during the cardiac cycle compared to the left anterior descending and left circumflex artery.**

Conclusions **The in-vivo accuracy of three-dimensional intravascular ultrasound (3D IVUS) is significantly high regardless of the type of the coronary arteries or their particular geometrical and morphological characteristics. This finding further supports the applicability of the method for either diagnostic or investigational purposes.** ***Coron Artery Dis*** **17:545–551 © 2006 Lippincott Williams & Wilkins.**

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Introduction

In the recent years, intravascular ultrasound (IVUS) has become increasingly important in the imaging of coronary atherosclerosis. IVUS is a catheter-based technique that provides two-dimensional (2D) high-resolution tomographic images of coronary arteries and, therefore, accurate information concerning plaque area and composition [1]. In addition, IVUS enables the three-dimensional (3D) reconstruction of coronary arteries permitting the reliable calculation of plaque volume. Routinely, such 3D reconstructions are performed linearly by stacking of adjacent IVUS frames [2]. This approach, however, completely ignores both the vessel curvature and the axial movements of the catheter during the pullback, restricting the accuracy of the reconstruction [3]. To overcome these limitations, a new imaging technique (3D IVUS) has been introduced, combining the 3D geometrical information obtained by biplane angiography with the volumetric information derived by IVUS, resulting in geometrically correct 3D reconstruction of coronary arteries. Three-dimensional IVUS is based on the principle that the angiographic data provide information

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about the spatial trajectory of the IVUS catheter, served as the 'backbone', on which the IVUS tomographic images are positioned and orientated in space. This technique has been previously described in depth and validated in vessel phantoms [3], as well as in ex-vivo [3–5] and in-vivo [4,6] human studies, revealing high accuracy and reproducibility [7].

In recent years, 3D IVUS has been proved to be a very useful tool in the investigation of coronary atherosclerosis. The range of its applications is broad and includes the realistic plaque morphometric analyses [8], the customized planning of intracoronary brachytherapy [9] and the evaluation of the impact of pharmaceutical or mechanical (e.g. stent) interventions on plaque progression and regression [8]. Its main potential, however, involves the study of the effect of geometrical (e.g. curvature, torsion) [10,11] and hemodynamic factors (e.g. shear stress, tensile stress) [12] on atherogenesis and plaque progression.

Coronary angiography is regarded as the gold standard imaging modality for atherosclerosis. It is well established, however, that its diagnostic accuracy is limited by several factors involving the poor imaging resolution and the geometrical distortions due to the magnification or vessel overlapping [13]. Recently, new imaging techniques, namely computed tomography and magnetic resonance imaging, have been gaining ground as they have great potential for non-invasive imaging of atherosclerotic plaques [14]. As for angiography, the imaging quality is restricted by the coronary motion, which is more prominent in the right coronary artery (RCA) than in the left anterior descending (LAD) or the left circumflex (LCx) [11].

Thus, the pulsatile nature of the heart, which influences the coronary motion, along with the complex 3D coronary geometry constitute a significant impediment towards the accurate, either invasive or non-invasive, imaging of the coronaries, and therefore they should be considered whenever a new imaging modality is developed. Given that the bibliography relevant to 3D IVUS lacks such information, we conducted the present study in order to investigate whether the type of coronary artery that mirrors the heart motion effect or the 3D configuration of the coronaries affect the accuracy of the reconstruction technique. The ultimate purpose of this study was to explore and reveal the potential characteristics of the coronary arteries that could restrict the applicability of 3D IVUS, so that those who use this method are aware of these limitations.

Methods

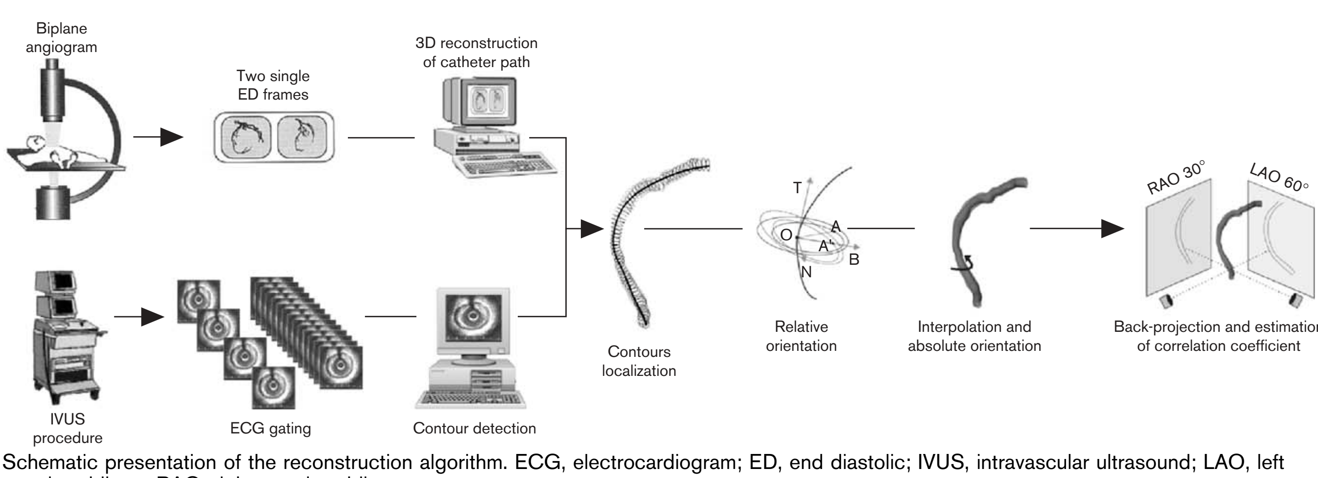
Study population

In total, 17 arterial segments (RCA, $n = 7$; LAD, $n = 4$; LCx $n = 6$) derived from nine patients were examined. All patients were randomly selected during routine interventional procedures for either diagnostic or therapeutic purposes. From the investigated arteries, eight had major lesions in angiography requiring mechanical intervention with stent while the remaining nine segments had no significant lesions. The institutional Medical Ethics Committee approved this study and all the participants gave written informed consent.

Reconstruction algorithm

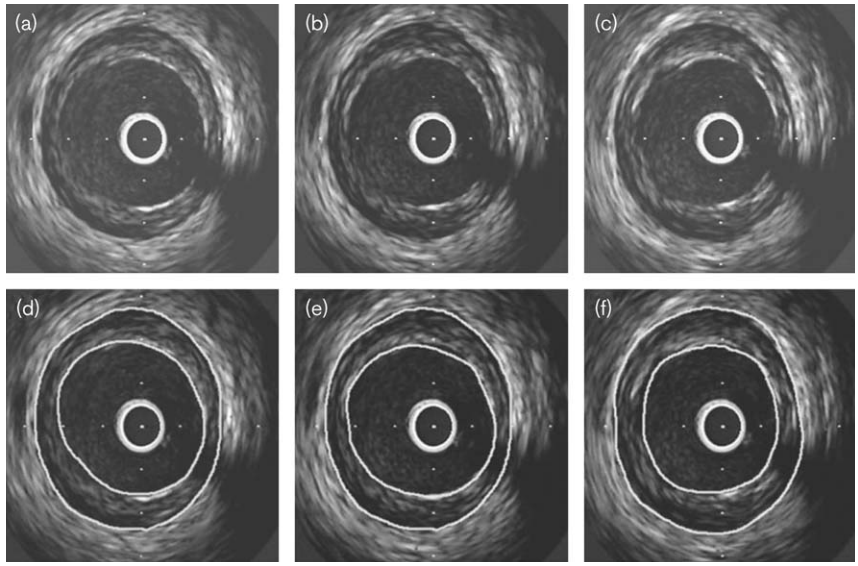
The reconstruction algorithm has been described analytically elsewhere [3–7] and is presented schematically in Fig. 1. Briefly, the IVUS catheter was inserted through a 6 F guiding catheter into the investigated coronary artery. With the catheter at its most distal location, a biplane

Fig. 1



Schematic presentation of the reconstruction algorithm. ECG, electrocardiogram; ED, end diastolic; IVUS, intravascular ultrasound; LAO, left anterior oblique; RAO, right anterior oblique.

Fig. 2



A sample of three consecutive images before (a–c) and after (d–f) the application of the semi-automated segmentation.

coronary angiogram was recorded. From each angiographic projection [right anterior oblique (RAO) 30° and left anterior oblique (LAO) 60°], a single end-diastolic frame was selected corresponding to the peak of R-wave on the electrocardiogram. On the basis of the course of the IVUS catheter in each angiographic projection, the 3D trajectory of the pullback was reconstructed [6].

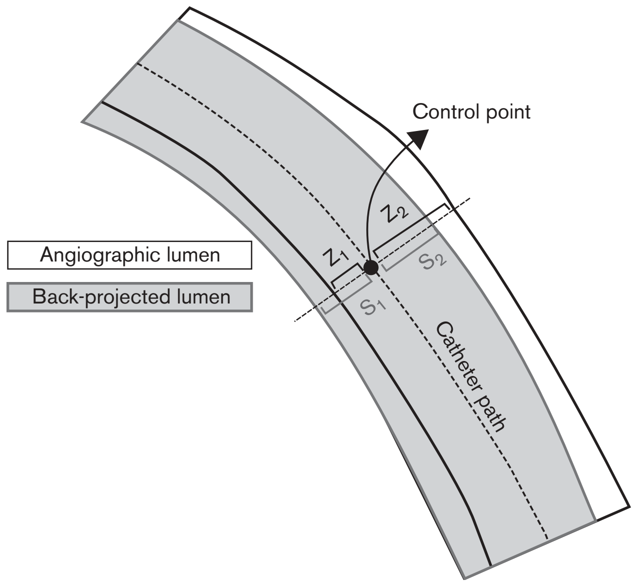
The IVUS procedure was performed with a mechanical imaging system (ClearView; Boston Scientific, Natick, Massachusetts, USA) and a 2.6 F sheath-based catheter, incorporating a 40 MHz single-element transducer and yielding 30 images/s (Atlantis SR Pro; Boston Scientific). A motorized pullback device was used to withdraw the catheter from its most distal point to the outlet of the guiding catheter at a constant speed of 0.5 mm/s. The ultrasound data were digitized by a frame–grabber and the end-diastolic images were selected. Then, the lumen and media–adventitia borders [1] were detected semi-automatically in the selected sequence of end-diastolic IVUS images by a custom-developed computer algorithm based on active contour models [6,15,16]. Figure 2 presents a sample of three consecutive images before (a–c) and after (d–f) semi-automated segmentation.

All the pairs of the detected contours (luminal and media–adventitia) were assigned perpendicularly onto the 3D catheter. The correct position of each pair was calculated by the known identical frame number, the pullback speed and the frequency of the frame acquisition. For the purpose of the present analysis, these points were considered to be the *control points* (Fig. 3). As the angular rotation of the IVUS catheter during pullback could distort the real geometry of the reconstructed artery, the correct rotational orientation of the luminal contours was determined by applying a Frenet–Serret theorem-based algorithm reported elsewhere [3] (Fig. 1).

Measurement of the method's accuracy

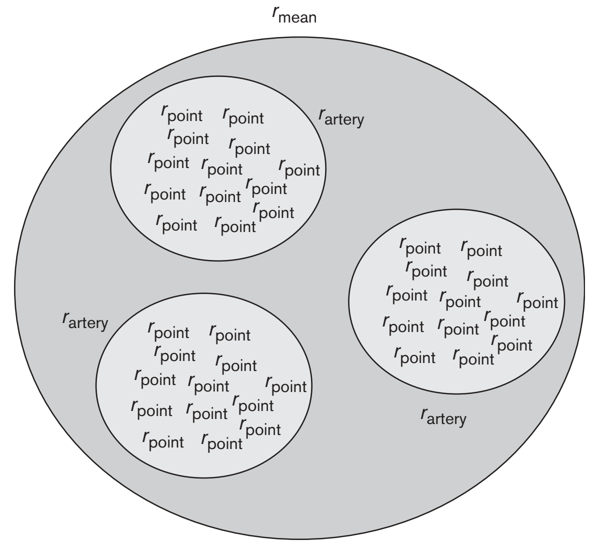
The correctly orientated luminal and media–adventitia contours were interpolated with additional intermediate contours, generating a 3D lumen and vessel volume, respectively. To determine the spatially correct orientation of the entire reconstructed vessel, the lumen was rotated iteratively searching for the best possible match with the corresponding angiographic luminal edges. This was accomplished through a custom-developed automated algorithm (Matlab; The MathWorks Inc., Natick, Massachusetts, USA) by back-projecting the reconstructed lumen onto each angiographic plane and comparing the projected with the angiographic luminal outlines, considering the angiographic outlines as reference. The concept of this algorithm is presented briefly (Fig. 3). In each angiographic projection, the distances between the catheter path and the angiographic luminal outlines (Z_1 and Z_2) were measured at each control point (black dot in Fig. 3) and considered as variable X. Then, the entire set of contours was rotated consecutively by 2° to complete a full circle (180 rotations). In each angle of rotation, the IVUS reconstructed lumen was back-projected onto the angiographic planes and the corresponding distances between the catheter path and the

Fig. 3



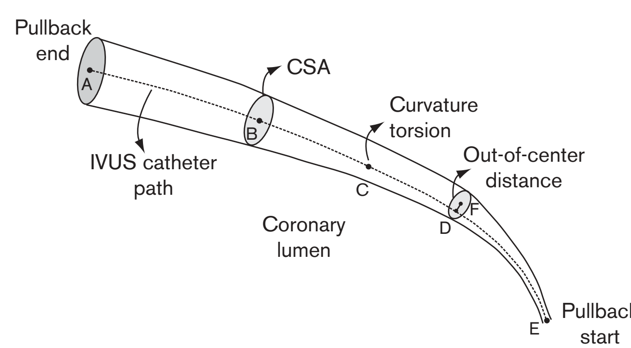
Schematic presentation of the matching between the reconstructed lumen (defined by the gray line) back-projected onto each angiographic plane and the actual lumen (defined by the black line). The angiographic luminal outlines were considered as reference. In each plane, the distances between the catheter trajectory (dashed black line) and the detected luminal outlines (Z_1 and Z_2) were measured at each control point (black dot) and considered as variable *X*. Then, the corresponding distances between the catheter path and the back-projected luminal edges (S_1 and S_2) were calculated, thus creating random variables Y_i (i=1,..., 180). The mean correlation coefficient between Z_1 vs. S_1 and Z_2 vs. S_2 at each control point determined the control point correlation coefficient (r_{point}).

Fig. 4



The control point correlation coefficient (r_{point}), the artery correlation coefficient (r_{artery}) and the mean correlation coefficient (r_{mean}) were used as measures of the agreement between the reconstructed lumen and the actual angiographic lumen. The r_{artery} was derived by the mean of all the r_{point} in each artery, while the r_{mean} was the mean of all the r_{artery}. The higher these coefficients the better the matching between the reconstructed and the angiographic lumen and thus the higher the accuracy of the method.

Fig. 5



Schematic presentation of the calculated geometrical and morphologocal characteristics of the three-dimensional reconstructed lumen; namely, the lumen's length, defined as the length of the catheter (black dashed line) from the pullback start (E) up to the pullback end (A), the luminal volume, the lumen cross-sectional area (CSA) (gray plane), the curvature and torsion at each control point (black dots, A–E) and the out-of-center distance (FD) defined as the distance between the centroid (F) of each cross-section and the corresponding control point (D). The out-of-center distance represented the degree of deviation of intravascular ultrasound (IVUS) catheter from the lumen's centerline.

projected luminal edges (S_1 and S_2) were calculated, thus creating variables Y_i ($i=1,\ldots,180$). Hence, at each control point four distances were measured for every rotational angle. These distances were correlated with each other (Z_1 vs. S_1 and Z_2 vs. S_2 at RAO 30°; Z_1 vs. S_1 and Z_2 vs. S_2 at LAO 60°) and their mean correlation coefficient determined the *control point correlation coefficient* (r_{point}). Moreover, in each reconstructed lumen the mean correlation coefficient between the random variables *X* and Y_i was defined as the *artery correlation coefficient* (r_{artery}). In other words, in each artery the r_{artery} was the mean of all the r_{point} (Fig. 4). The angle with the maximum r_{artery} determined the best possible match between the angiographic and back-projected lumen on both projections. The overall quantitative accuracy of the reconstruction method was derived from the *mean overall correlation coefficient* (r_{mean}), the mean of r_{artery} of all the reconstructed arteries ($n=17$) (Fig. 4).

Calculated parameters

After determining the correct spatial position of the reconstructed artery based on the above-mentioned approach, we assessed the effect of several parameters on the accuracy of our reconstruction method. In order to detect this accuracy in each category of coronary arteries, the reconstructed arteries were divided into three groups, namely LAD ($n=4$), LCx ($n=6$) and RCA ($n=7$); the *mean group correlation coefficient* (r_{group}) in each group, which in fact was the mean of r_{artery} of the arteries comprising each group, was compared with each other.

Additionally, in each reconstructed artery several specific geometrical and morphological characteristics that might influence the accuracy of the method were calculated; namely, the length (l) of the artery and the volume (V) of the lumen. Further, in each control point the luminal cross-sectional area (CSA), the catheter's curvature (k), torsion (t) and the out-of-center distance of the catheter (c) were evaluated. The curvature and torsion described the 3D course of the catheter, defining its degree of deviation from straightness and plainness, respectively [10,11]. The out-of-center distance represented the degree of deviation of IVUS catheter from the lumen's centerline. All the above parameters are analytically presented and defined in Fig. 5. Using r_{point} and r_{artery} as measures of the agreement between the reconstructed lumen and the actual angiographic lumen, and therefore as measures of the reconstruction method's accuracy, the influence of the above-mentioned geometrical parameters was determined quantitatively in the following fashion: the l and V were correlated with r_{artery} of each artery, while the values of CSA, k, t and c at each control point were correlated with the corresponding r_{point}. This approach enabled us to investigate the effect of regional (point by point) geometrical characteristics on the method's accuracy. The possible finding of significant association with these variables would imply that the method lacks accuracy in arterial segments with such characteristics.

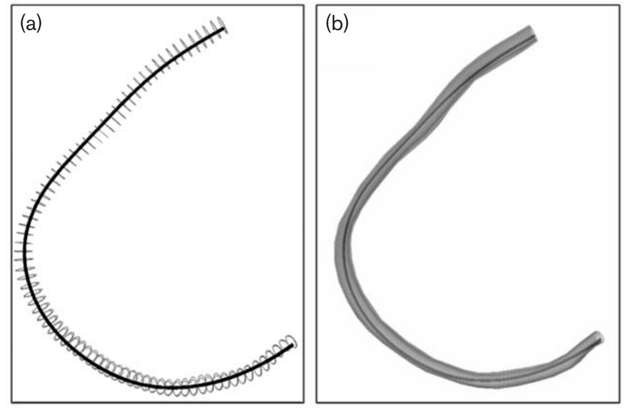
Statistical analyses

Data analyses were performed with the statistical package SPSS 12.0 (SPSS Inc. Chicago, Illinois, USA). All results were expressed as mean ± SD, whereas $P < 0.05$ was considered as the level of significance. The comparisons of r_{mean} among the arterial groups (LAD, LCx and RCA) were performed with one-way analysis of variance (ANOVA). Provided that the distances did not fulfil the assumption of normality, which is a quite common finding in large data samples, the association between the reconstructed lumen and the corresponding angiographic lumen was examined with Spearman's correlation coefficient. Spearman's correlation coefficient was also used for the correlation of l and V with r_{artery}, while the correlations of CSA, k, t and c with r_{point} were measured by Pearson's correlation coefficient.

Results

The reconstruction method was successfully implemented in all the coronary arteries ($n = 17$) regardless of their burden of atherosclerosis. Figure 6 illustrates a 3D reconstructed RCA segment. For each artery,

Fig. 6



A three-dimensional (3D) reconstructed right coronary artery. (a) The lumen and media–adventitia contours were located on the 3D intravascular ultrasound (IVUS) catheter path and spatially orientated. (b) The 3D lumen along with the wall was created with interpolation of the lumen and media–adventitia contours, respectively. This particular view is transparent so that the IVUS catheter within the lumen can be visible.

1286 ± 257 (range, 809–1653) IVUS images were recorded, from which 199 ± 52 (range, 126–287) end-diastolic ones were selected. In total, 929 control points were assigned in all the reconstructed vessels, thus 929 control point correlation coefficients (r_{point}) were calculated, while the mean number of control points for each artery was 57.3 ± 10.7 (range, 40–80).

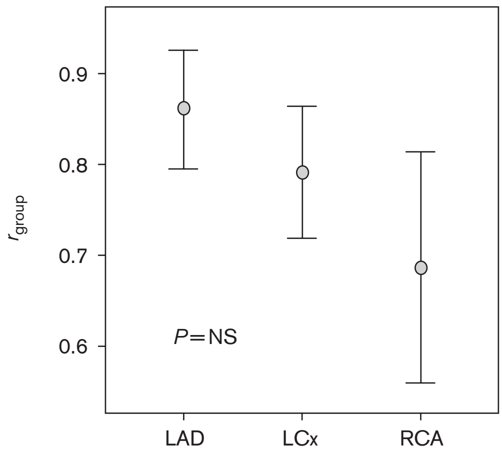
Effect of coronary type

The mean overall correlation coefficient (r_{mean}) between the reconstructed lumens and the actual angiographic ones was found to be 0.78 ($P < 0.001$), revealing a good accuracy for the method. With regards to each arterial group, the mean group correlation coefficients (r_{group}) were 0.86, 0.79 and 0.70 for LAD, LCx and RCA, respectively. Although the r_{group} for LAD (0.86 ± 0.66, $n = 4$) was greater than that for LCx (0.79 ± 0.89, $n = 6$) and RCA (0.69 ± 0.17, $n = 7$), one-way analysis of variance did not reveal any significant differences among them (Fig. 7).

Effect of geometrical and morphological factors

Table 1 shows the mean values of the calculated geometrical and morphological parameters for all the reconstructed arteries. No significant association was found between r_{artery} and l, V as well as r_{point} and CSA, k, t and c, suggesting that the reconstruction method was accurate in the entire length of the reconstructed arteries regardless of their regional geometrical particularities.

Fig. 7



The mean group correlation coefficient (r_{group}) of left anterior descending (LAD), left circumflex (LCx) and right coronary artery (RCA) used as measure of the reconstruction method's accuracy in each category of artery. Each line represents the range of values between the mean ± SD with the mean shown as a gray dot. No significant differences were found between these correlation coefficients. The reconstruction method, however, exhibited slightly less mean correlation coefficient and thus accuracy in the reconstruction of RCA compared with LCx and LAD, possibly due to the more intense pulsatile motion that RCA experiences during the cardiac cycle.

Table 1 Mean values of the calculated geometrical and morphological parameters all the reconstructed arteries

Parameters	
Length, l (mm)	85.6 ± 17.1
Volume, V (mm^3)	620.8 ± 195.3
Cross-sectional area (mm^2)	7.05 ± 3.44
Curvature, k (mm^{-1})	0.038 ± 0.052
Torsion, t	0.003 ± 0.288
Out-of-center distance, c (mm)	0.58 ± 0.31

All values are expressed as mean ± SD.

Discussion

In this study, we applied a well-described imaging technique for the in-vivo geometrically correct 3D reconstruction of human coronary arteries based on the integration of IVUS and biplane angiography [3–7]. Our primary purpose was to investigate whether the type of coronary arteries or the 3D configuration of the coronaries limit the diagnostic accuracy of this technique. In the setting of the increased application of this method in patient-based computational studies, a better understanding of the accuracy of anatomical reconstruction is crucial and such information is missing from the contemporary literature.

The overall accuracy of our method as measured by the degree of matching between the back-projected reconstructed lumens and the actual angiographic ones was found to be high ($r = 0.78$, $P < 0.001$). This was in good agreement with the corresponding value of 0.84 found elsewhere [4], suggesting that the methodology we implemented in the present analysis was valid. In addition, for the segmentation of IVUS images a semi-automated algorithm was applied, which was extensively well validated in other similar studies [5,6,16].

In the present work, we investigated the accuracy of 3D IVUS in the major coronary arteries (LAD, LCx and RCA). We used the degree of overlapping between the reconstructed lumen back-projected onto the angiographic planes and the actual lumen delineated on each plane as an indicator of the accuracy of our method. The reliability of this indicator has been reported elsewhere [4]. According to our results, the method experienced good accuracy in all the coronary groups, although there was a strong tendency to be more accurate in LAD and LCx than in RCA. This discrepancy could be attributed to the fact that RCA exhibits twofold and more rapid diastolic motion than the LAD and LCx, probably due to its particular position on the cardiac surface [11]. This particular motion is mainly caused by the atrial contraction that occurs during the end-diastole [11]. Similarly, in most of the recent computed tomography studies the results for RCA with regard to the image quality were worse than those for LAD [14,17,18]. As mentioned, the difference in our method's accuracy among the coronary arteries was not significant; thus, 3D IVUS could reliably be applied in all the coronary arteries although a slight degree of limitation in the case of RCA should always be considered.

Apart from the complex movements of the IVUS catheter in relation to the coronary vessel during the cardiac cycle, which potentially limits the diagnostic accuracy of the reconstruction method, several geometrical and morphological parameters of the coronaries, namely the luminal length and volume as well as the lumen cross-sectional area, the curvature, the torsion and the out-of-center distance of the catheter could potentially influence this accuracy as well. Hence, we investigated whether these factors, affect the reliability of the method, and if so in what fashion. According to our results, for all the calculated parameters no significant correlation between the control point correlation coefficient or artery correlation coefficient and each parameter individually was found. These findings imply that 3D IVUS has the potential to accurately reconstruct the entire length of the coronary artery regardless of the presence of stenoses or segments with particular geometric irregularities such as high curvature and torsion. Similarly, the deviation of the pullback trajectory from the vessel centerline, as reflected by the out-of-center distance of the catheter, does not seem to influence the final reconstruction.

Study limitations

Several limitations exist in our study. First, the limited number of cases does not enable us to generalize our results. Furthermore, the current analyses and conclusions are confined to IVUS imaging systems using sheath-based catheters, which secure a steady pullback trajectory. Another limitation was that, although we considered that the catheter's length corresponds to the artery's length, in fact the actual artery's length was equal to the length of its centerline. This is because the catheter did not pass through the centerline of the vessel during its pullback but follows a slightly different course defined by the vessel's curvature [4]. Such an error, however, seems to be minimal without influencing the reliability of our outcome.

Conclusions

The in-vivo spatially correct 3D reconstruction of the human coronary arteries constitutes an imaging method based on the integration of two existing imaging modalities, namely the biplane angiography and IVUS. Both its applicability and its accuracy have been found to be significantly high regardless of the category of the reconstructed artery and its distinct geometrical and morphological characteristics. This finding further supports the applicability of the method for either diagnostic or investigational purposes.

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