In Vivo Comparative Study of Linear Versus Geometrically Correct Three-Dimensional Reconstruction of Coronary Arteries

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Although conventional linear 3-dimensional (3D) reconstruction of coronary arteries by intravascular ultrasound has been widely used for the assessment of plaque volume and progression; the volumetric error (VE) that is produced has not been adequately studied. Linear and geometrically correct 3D reconstruction was applied in 16 coronary arterial segments from 9 patients. Using geometrically correct reconstruction as reference, VE was assessed in 1-mm-long arterial slices. Although for the entire length of the coronary arteries VEs for lumen, external elastic membrane (EEM), and intima-media volumes were minimal (lumen VE 0.4%, −0.8 to 1.8; EEM VE 0.3%, −0.9 to 1.9; intima-media VE 0.4%, −1.4 to 2.2), the VE in each arterial slice exhibited a large variation from −15.6% to 36.2% for lumen volume, from −12.9% to 33.1% for EEM volume, and from −17.2% to 46.7% for intima-media volume, suggesting that linear reconstruction over- or underestimates the true arterial volumes. Lumen VE, EEM VE, and intima-media VE were also significantly higher in curved arterial subsegments than in relatively straight arterial subsegments (p <0.05). In conclusion, in highly curved arterial subsegments, the VE that is produced by linearly stacking the intravascular ultrasound images may be not negligible. Geometrically correct reconstruction of coronary arteries provides more reliable arterial reconstructions and plaque volume measurements. It is anticipated that clinical application of this technique will contribute to more accurate follow-up of the progression of atherosclerosis and assessment of arterial remodeling. **(Am J Cardiol 2008;101:263–267)**

Intravascular ultrasound (IVUS) has been widely used for assessment of the progression of coronary atherosclerosis and the nature of vascular remodeling in large clinical trials.[1] In these trials IVUS volumetric measurements have been routinely performed by linear stacking of adjacent IVUS images and summing the plaque areas of those images.[2,3] However, the complex 3-dimensional (3D) geometry of coronary arteries, which is characterized by curvatures of different degrees, is very likely to produce an error in the IVUS volumetric measurements.[4,5] Geometrically correct 3D reconstruction of coronary arteries is an imaging technique that combines biplane angiography with IVUS to provide accurate[2,4,6–8] and reproducible[9] representations of coronary arterial geometry. The purpose of this study was to investigate the volumetric error (VE) that is produced by conventional linear 3D reconstruction of coronary arteries and to explore arterial geometric and morphometric factors that influence this VE. Geometrically correct 3D reconstruction was used as the reference technique in our analyses.

Methods

Sixteen arterial segments (right coronary artery, n = 6; left anterior descending, n = 4; left circumflex, n = 6) from 9 patients were examined with angiography and IVUS (ClearView, Boston Scientific, Natick, Massachusetts). The institutional Medical Ethics Committee approved the study and written informed consent was obtained from all participants.

Geometrically correct 3D reconstruction of coronary arteries was previously described in detail.[4,6–9] In brief, IVUS was performed with a 40-MHz sheath-based catheter rotating at 1,800 rpm and yielding 30 images per second. Automated pullback of the catheter was performed at a constant speed of 0.5 mm/s. The physical 3D path of the IVUS catheter during the pullback was determined using corresponding biplane angiographic projections. Lumen and external elastic membrane (EEM) borders were semiautomat-

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ically identified in digitized, end-diastolic, IVUS images using a computer algorithm based on active contours.[10] Each IVUS image was positioned perpendicularly onto the reconstructed catheter path and orientated in space.[7] Lumen and EEM borders of each IVUS image were connected with the corresponding borders of adjacent IVUS images using b-spline curves to rebuild the real arterial geometry in space. The resulting 3D volume was rotated appropriately to match the actual angiographic projections.[7]

For the linear 3D reconstruction of coronary arteries, the 3D path of the IVUS catheter was considered as straight and the end-diastolic IVUS images were perpendicularly assigned on specific locations along that straight catheter path.[2] Lumen and EEM contours of each IVUS image were then connected with the corresponding borders of adjacent IVUS images using b-spline curves, creating a linear 3D arterial geometry.

Geometrically correct and linear arteries were subdivided into 1-mm-long slices, such that each slice in the geometrically correct reconstruction had a corresponding slice of the same length in the linear reconstruction. To investigate the volumetric agreement between geometrically correct and linear reconstructions, lumen volume, EEM volume, and intima-media volume (IMV) in geometrically correct reconstructed slices were compared with the corresponding volumes in linearly reconstructed slices using geometrically correct reconstruction volumes as reference. The VE for lumen volume, EEM volume, and IMV between geometrically correct and linear 3D reconstructions was calculated in each slice using the formula VE = ([slice volume in geometrically correct reconstruction − slice volume in linear reconstruction])/slice volume in geometrically correct reconstruction) × 100%.[5]

The effect of coronary artery geometric and morphometric parameters on VE was also investigated. These parameters included lumen cross-sectional area, out-of-center distance of the IVUS catheter, and centerline curvature and torsion.[8] Out-of-center distance represented the vertical distance between the IVUS catheter and the centerline of the artery; the longer the out-of-center distance, the greater the deviation of the IVUS catheter from the centerline. Centerline curvature and torsion represented the course of the artery centerline in space; the greater the centerline curvature and torsion, the more curved and tortuous the artery.

We investigated whether the IVUS catheter follows the same course as the artery centerline by comparing the centerline curvature and torsion with the catheter curvature and torsion. No significant correlation was found between centerline curvature and catheter curvature (r = 0.06, p = 0.1), indicating that the IVUS catheter does not pass from the centerline of the artery but follows an independent course that is determined by arterial curvature. In contrast, centerline torsion and catheter torsion were well correlated (r = 0.42, p <0.001). Taking the differences between centerline and catheter curvature into account, we further explored the effect of centerline curvature on the magnitude of VE. Ten-millimeter-long curved and relatively straight subsegments were identified in each geometrically correct reconstructed artery and the VE was calculated. Curved subsegments were defined as those in which the centerline curvature was >0.2 mm^{-1} and straight subsegments as those in which the centerline curvature was <0.1 mm^{-1}.

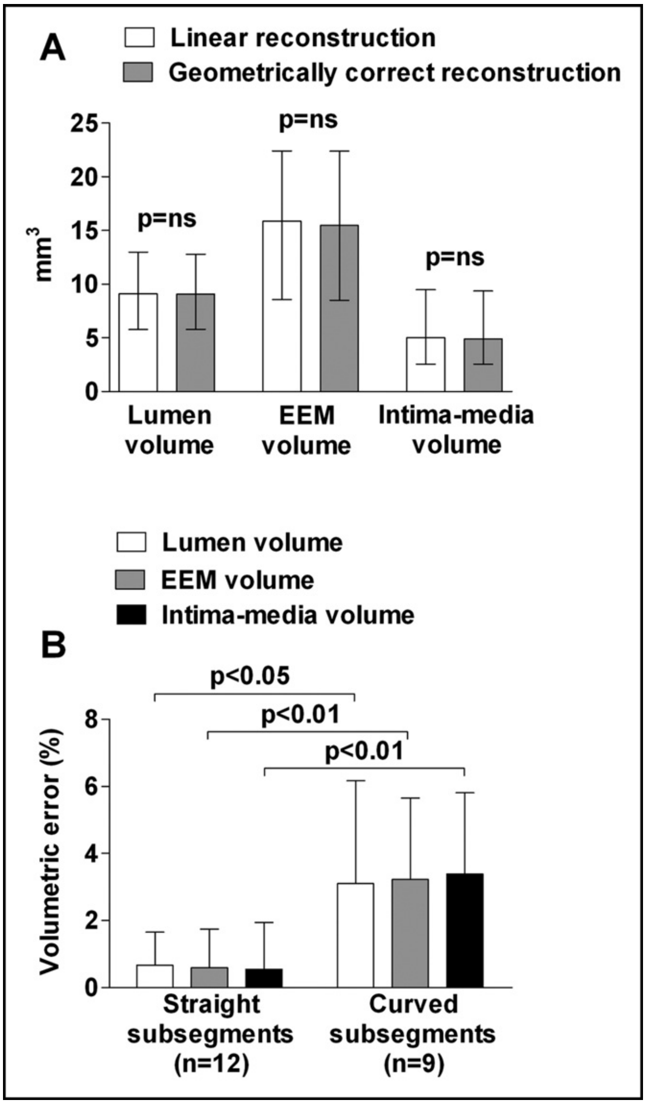

Figure 1. *(A)* Median lumen volume, EEM volume, and IMV in linear versus geometrically correct arterial reconstructions. *(B)* Mean lumen VE, EEM VE, and intima-media VE in straight and curved arterial subsegments.

Data analysis was performed with SPSS 12.0 (SPSS, Inc., Chicago, Illinois). A p value <0.05 was considered statistically significant. Continuous variables are summarized as mean ± SD or median and interquartile range, the latter representing values between the 25th and 75th percentiles of distribution. Comparison of means was performed with *t* test for independent samples or Mann-Whitney test as appropriate. Pearson and Spearman correlation coefficients were used for correlation of variables. Volumetric agreement and correlation between geometrically correct and linear 3D reconstructions were estimated by Bland-Altman analysis and linear regression analysis, respectively. Arterial geometric and morphometric parameters independently asso-

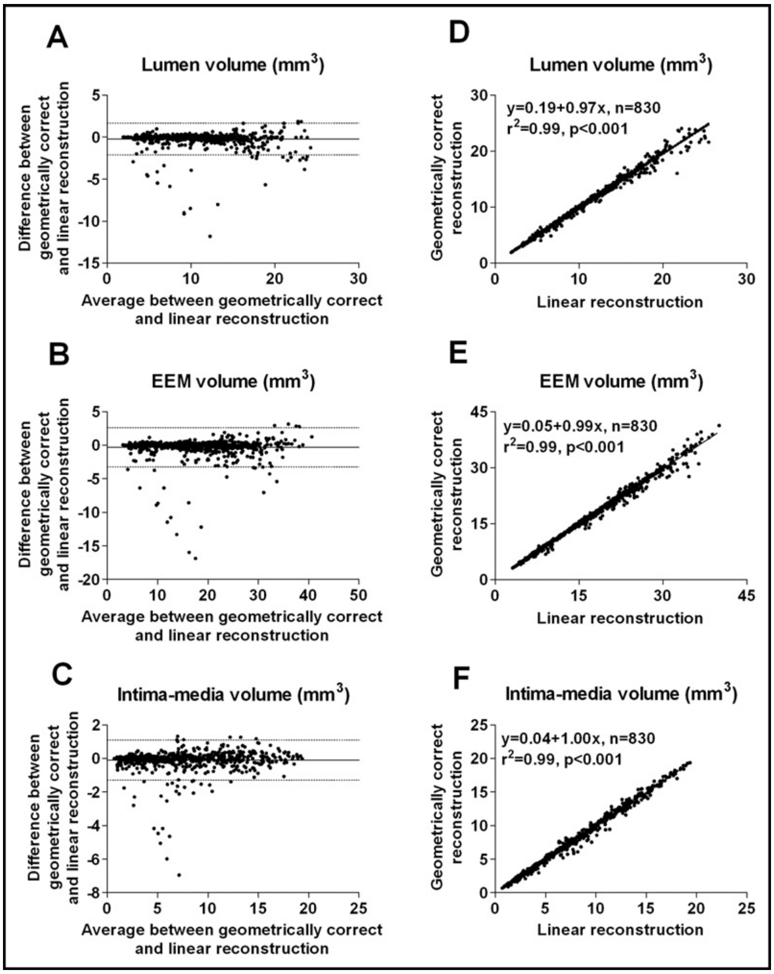

Figure 2. Bland-Altman plots *(A–C)* and linear regression plots *(D–E)* for lumen volume, EEM volume, and IMV.

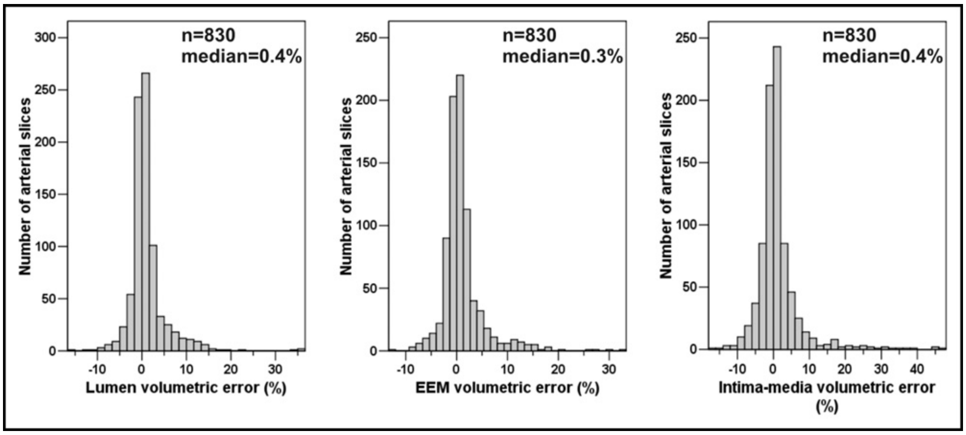

Figure 3. Frequency distribution of lumen VE, EEM VE, and intima-media VE.

ciated with lumen VE, EEM VE, and intima-media VE were identified by multivariate regression analysis.

Results

Eight hundred thirty slices were assigned in geometrically correct reconstructions, corresponding to an equal number of slices in linear reconstructions. There was a high volumetric agreement between geometrically correct and linear reconstructions for lumen volume (9.1 mm^3, 5.8 to 12.8, vs 9.1 mm^3, 5.8 to 13.0, p = NS), EEM volume (15.5 mm^3, 8.5 to 22.4, vs 15.9 mm^3, 8.6 to 22.4, p = NS), and IMV (4.9 mm^3, 2.5 to 9.4, vs 5.0 mm^3, 2.6 to 9.5, p = NS; Figure 1). This volumetric agreement was also demonstrated by Bland-Altman and linear regression analyses (Figure 2).

Table 1
Linear regression analysis of independent predictors of lumen, external elastic membrane, and intima-media volumetric errors

Variables	Lumen Cross-sectional Area		Out-of-center Distance		Centerline Curvature		Centerline Torsion	
	B	p Value	B	p Value	B	p Value	B	p Value
Lumen VE (n = 830)	−0.106	0.034*	1.100	0.034*	8.062	0.000*	−0.020	0.830
EEM VE (n = 830)	−0.125	0.013*	0.875	0.091	7.341	0.000*	−0.026	0.771
Intima-media VE (n = 830)	−0.190	0.015*	0.361	0.657	5.930	0.000*	−0.057	0.691

* $p < 0.05$.

With regard to the VE, this was minimal when considering all arterial slices in the analysis (lumen VE 0.4%, −0.8 to 1.8; EEM VE 0.3%, −0.9 to 1.9; intima-media VE 0.4%, −1.4 to 2.2; Figure 3). Despite the lack of substantial VE on the aggregate analysis, the VE in each slice exhibited a large variation from −15.6% to 36.2% for lumen volume, from −12.9% to 33.1% for EEM volume, and from −17.2% to 46.7% for IMV, indicating that linear reconstruction overestimates or underestimates the true arterial volumes (Figure 3).

To investigate the effect of arterial geometric and morphometric parameters on lumen VE, EEM VE, and intima-media VE, multivariate regression analysis was performed (Table 1). Centerline curvature was positively associated with lumen VE, EEM VE, and intima-media VE, whereas lumen cross-sectional area was negatively associated with lumen VE, EEM VE, and intima-media VE. There was also a positive association between out-of-center distance of the IVUS catheter and lumen VE.

To further explore the effect of artery curvature on VE, highly curved and relatively straight arterial subsegments were identified in geometrically correct segments. Nine curved and 12 straight subsegments were identified (length 8.9 ± 2.5 vs 11.6 ± 5.2 mm, p = NS; centerline curvature 0.25 mm^{-1}, 0.17 to 0.40, vs 0.05 mm^{-1}, 0.03 to 0.06, $p < 0.05$). Lumen VE, EEM VE, and intima-media VE were significantly higher in curved subsegments than in straight subsegments (lumen VE 3.10 ± 3.07% vs 0.67 ± 0.98%, $p < 0.05$; EEM VE 3.22 ± 2.43% vs 0.59 ± 1.15%, $p < 0.01$; intima-media VE 3.39 ± 2.42% vs 0.55 ± 1.39%, $p < 0.01$; Figure 1).

Discussion

In this study we investigated in vivo the VE that is produced in routine IVUS volumetric measurements, in which the pullback is considered linear and the acquired IVUS images are positioned along a straight line. These volumetric measurements were compared with the true volumes derived by geometrically correct 3D reconstruction of the same arterial segments. Although for the entire length of the coronary arteries a high volumetric agreement for lumen volume, EEM volume, and IMV between linear and geometrically correct reconstructions was observed, segmental analysis revealed that the VE is higher in highly curved subsegments than in relatively straight subsegments.

IVUS has become an important tool in the diagnosis and assessment of the severity and progression of coronary atherosclerosis.[1] In clinical practice volumetric measurements are typically performed in linearly reconstructed coronary arteries, neglecting the true spatial configuration of the arteries.[3] Consequently, some degree of VE is likely to be produced. Investigations in arterial phantoms and ex vivo studies in human coronary arteries indicated that the VE is dependent on arterial curvature varying from 1% to 35%.[11,12] However, these studies did not address the VE of in vivo IVUS measurements. An in vivo study in human coronary arteries used geometrically correct 3D reconstruction as reference and demonstrated that intima-media VE varies from −1.2% to 2.3% (mean 0.73) and is positively associated with catheter curvature, such that the greater the curvature of the IVUS catheter, the higher the VE.[5] However, the effect of true arterial curvature on intima-media VE and on lumen VE and EEM VE, which are important components in the assessment of arterial remodeling, has not been studied. In the present study we found that, although the VE that is produced with linear 3D reconstruction is quite minimal when calculated for the entire length of the artery, it may not be negligible when measurements are performed in a small arterial subsegment; lumen volume, EEM volume, and IMV may be overestimated by up to 36%, 33% and 47%, respectively.

We further investigated local arterial morphometric and geometric factors that may influence local VE and we demonstrated that in arterial subsegments with increased curvature the linear reconstruction overestimates true lumen volume, EEM volume, and IMV by 3.1 ± 3.07%, 3.2 ± 2.4%, and 3.4 ± 2.4%, respectively, whereas the corresponding VE in straight subsegments is minimal. Large prospective IVUS studies,[13,14] in which linear reconstruction was applied for volume measurements, have demonstrated that the mean rate of progression or regression of plaque volume after 18 or 24 months of follow-up varies from 0.4% to 6.8% and therefore is of the same magnitude with the VE that was observed in curved arterial subsegments in our study. Therefore, although conventional volumetric measurements can reliably be performed in straight arterial subsegments, in highly curved subsegments the conventional measurement of plaque volume may provide false-positive results of atherosclerotic progression or regression. New methods currently exist for geometrically correct arterial reconstruction and clinical application of such methods is anticipated to contribute to more accurate follow-up of progression or regression of atherosclerosis and estimation of arterial remodeling.[15]

The small study population was a major limitation of our pilot study and larger studies need to be done to confirm our results. All volumetric analyses presented in our study refer to IVUS procedures that elaborate sheath-based IVUS catheters. Currently there are no data regarding the VE that is produced by electronic IVUS systems, which use free-floating catheters.[11]

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