MECHANICAL STRESS ANALYSIS IN CORONARY ATHEROSCLEROTIC PLAQUES: 2D VS. 3D COMPUTATIONAL APPROACHES

Sara Zambon (1), Aikaterini Tziotziou (2), Eline M.J. Hartman (2), Claudio Chiastra (1), Joost Daemen (2), Umberto Morbiducci (1), Jolanda J. Wentzel (2), Diego Gallo (1)

1. Politecnico di Torino, Italy; 2. Erasmus MC, the Netherlands

Introduction

Biomechanical factors play a fundamental role in the initiation and progression of coronary atherosclerotic plaques. Recent evidence suggests a link between elevated mechanical wall stress (MWS) and (i) a reduction in the size of lipid-rich necrotic core (LRNC) within atherosclerotic plaques, and (ii) the development of wall thickening in plaque-free regions [1]. Additionally, high MWS "hot spots" may contribute to plaque rupture [2]. Most of these findings rely on finite element (FE) 2D structural analyses, which may oversimplify the complex 3D structure of the atherosclerotic arterial wall. To enhance the current methodology, this study compares 2D *vs.* 3D FE-based modelling approaches to evaluate MWS distribution in atherosclerotic coronary lesions with LRNC.

Methods

Six acute coronary syndrome patients underwent invasive pressure measurement, computed tomography angiography (CTA), optical coherence tomography (OCT), and intravascular ultrasound (IVUS) imaging of a non-culprit coronary artery (three left anterior descending coronary arteries, LAD, and three right coronary arteries, RCA) [1]. Combining co-registered IVUS and OCT frames, a total of 216 2D cross-sections were obtained, including 24 containing LRNC. Lumen and external elastic lamina were segmented from IVUS images. The adventitia was assumed to have constant thickness [1]. The LRNC inner edge was segmented on OCT images, while the outer edge was reconstructed adopting a previously validated approach [3]. The 3D geometry was reconstructed combining lumen contours segmented from IVUS and the vessel centerline extracted from CTA images. FE-based structural simulations were carried out in Abaqus/Standard (Dassault Systèmes), assuming intima and media, adventitia, and LRNC components as nonlinear hyperelastic materials [1]. The backward incremental method [4] was applied to obtain the initial diastolic stress distribution before prescribing the patient-specific systolic blood pressure. The 2D vs. 3D comparison was carried out in terms of von Mises stress (VMS) distributions, maximum luminal VMS values, and angular distance between the locations of maximum luminal VMS. In the cross-sections containing LRNC, the cap VMS distributions and maximum values were also assessed. Additionally, a strategy was considered in which the systolic stress distribution in 2D FE simulations was computed from the diastolic stress distribution obtained in the 3D geometries. This approach was referred to as $2D_{init}$.

Results

In general, 2D simulations overestimated the maximum luminal VMS values compared to 3D simulations, with a median absolute difference of 48.3 kPa [interquartile range, IQR: 24.9-126.6 kPa]. The angular distance between the lumen locations of maximum VMS in 2D *vs.* 3D simulations was 6.6° [IQR: 2.9°-21.9°]. Bland-Altman analysis of 2D *vs.* 3D maximum luminal VMS yielded a bias of 86.8 kPa. Maximum luminal VMS values obtained from 2D and 3D simulations were linearly correlated (r=0.87, p<0.001). In the cap region, maximum VMS values from 2D simulations showed a bias of 97.3 kPa compared to 3D simulations (Fig.1) and a significant correlation (r=0.80, p<0.001, Fig. 1). The comparison between 3D and $2D_{init}$ strategies revealed VMS differences similar to those observed in the 2D *vs.* 3D comparison (luminal VMS absolute difference 59.5 kPa [IQR: 31.5-129-9 kPa]), in general exhibiting stronger correlations (r=0.91, p<0.001).

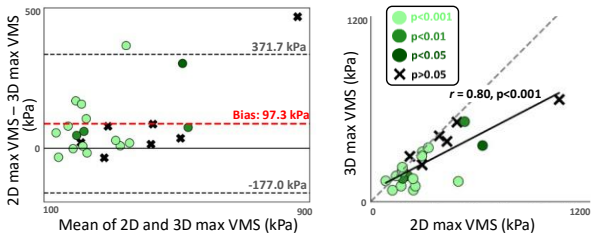

Fig.1: Bland-Altman (left) and scatter plot (right) of maximum VMS at the cap. The marker indicates the p-value obtained from Mann-Whitney tests comparing 2D vs. 3D distributions.

Conclusions

While 3D modelling provides a more realistic representation of the vessel, it requires data from a 3D imaging modality and entails higher computational costs. Although the 2D strategy may overestimate maximum VMS values at both the cap and lumen, it generally provides an accurate location of the maximum VMS. Our findings suggest that, despite the consistent bias, 2D FE-based analyses may offer a reasonable trade-off for investigating mechanical factors in coronary artery disease.

References

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