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FOCUS ISSUE ON BIFURCATION INTERVENTIONS

STATE-OF-THE-ART REVIEW

Biomechanical Modeling to Improve Coronary Artery Bifurcation Stenting

Expert Review Document on Techniques and Clinical Implementation

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ABSTRACT

Treatment of coronary bifurcation lesions remains an ongoing challenge for interventional cardiologists. Stenting of coronary bifurcations carries higher risk for in-stent restenosis, stent thrombosis, and recurrent clinical events. This review summarizes the current evidence regarding application and use of biomechanical modeling in the study of stent properties, local flow dynamics, and outcomes after percutaneous coronary interventions in bifurcation lesions. Biomechanical modeling of bifurcation stenting involves computational simulations and in vitro bench testing using subject-specific arterial geometries obtained from in vivo imaging. Biomechanical modeling has the potential to optimize stenting strategies and stent design, thereby reducing adverse outcomes. Large-scale clinical studies are needed to establish the translation of pre-clinical findings to the clinical arena. (J Am Coll Cardiol Intv 2015;8:1281–96) © 2015 by the American College of Cardiology Foundation.

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ABBREVIATIONS AND ACRONYMS

3D = 3-dimensional

CFD = computational fluid dynamics

CT = computed tomography

ESS = endothelial shear stress

ISR = in-stent restenosis

KBI = kissing balloon inflation

The advent of coronary artery stents has undoubtedly ushered a new era in interventional cardiology and revolutionized the therapeutic management of patients with coronary artery disease. However, despite significant advances, stents are known to have several shortcomings and more comprehensive insights into the complex in vivo stent-vascular interactions are required. A significant proportion of plaques develop in coronary bifurcation regions, and percutaneous interventions to such lesions account for one-fifth of all coronary interventions (1). Stents in bifurcations exhibit a predisposition to higher rates of in-stent restenosis, thrombosis, and recurrent adverse clinical events (2,3). Therefore, the interventional management of bifurcation lesions remains challenging and the ideal treatment strategy is still elusive.

Locally disturbed blood flow is a major determinant for the development and progression of atherosclerosis (4–6). In particular, low endothelial shear stress (ESS) provokes molecular, cellular, and vascular responses in atherosclerosis-prone sites, leading to plaque initiation and progression toward a more “vulnerable” profile via multiple mechanisms and interactions (7,8). A detailed quantitative appraisal of stent-induced alterations of blood flow following bifurcation stenting plays a key role in understanding this complex geometry (9). This information can facilitate the optimization of bifurcation stenting techniques, stent design, and subsequent reduction of adverse outcomes.

Studies in bifurcation stenting can be classified into computational simulations and in vitro bench testing. Computational simulations extend from idealized simple geometries to more complex anatomical representations of animal- and patient-specific coronary artery geometries obtained from in vivo imaging. Computer simulations can assess the local hemodynamic microenvironment in bifurcations pre- and post-stenting, providing an insight into the role of local hemodynamic stresses on neointimal hyperplasia and stent thrombosis. This review summarizes the current literature on the use of biomechanical modeling approaches to study stent properties, local flow dynamics in stented regions, and outcomes after percutaneous coronary interventions with particular emphasis on bifurcation stenting (**Central Illustration**). Animal studies correlating biomechanical modeling with histopathology findings as well as contemporary advances and challenges in patient-specific modeling for individualized decision making are also discussed.

COMPUTATIONAL SIMULATIONS FOR BIFURCATION STENTING OPTIMIZATION

RATIONALE AND GENERAL CHARACTERISTICS. Computational simulations offer indispensable information into the biomechanical effects of stenting and provide a framework for the quantitative assessment of mechanical stresses and blood flow dynamics in the diseased vascular segment (10–13). Mechanical simulations of stents enable virtual investigation of different bifurcation stenting techniques and can help to evaluate stenting outcomes. Recent advances in hardware and software have boosted the applicability and predictive accuracy of computer simulation studies in bifurcation stenting by diminishing the time required for geometry generation, pre-processing, numerical solution, and post-simulation data processing. Reconstruction of accurate geometries, realistic boundary conditions, and constitutive laws for material properties are essential for accurate computational studies (14). Whereas seminal reports in this field have employed idealized conceptual geometrical models (15,16), patient-specific models based on hybrid clinical coronary imaging data have emerged in the recent years (17–21). Processing of complex arterial geometries to fit a computational grid is not a trivial undertaking. A hybrid meshing method that combines tetrahedral and hexahedral elements has been adopted to reduce

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