Plaque mechanics

The deformation and stress distribution in plaques play an important role in various aspects of atherosclerotic disease. This special issue is composed of reviews and original research articles of the state-of-the-art, focusing on different topics that relate to plaque mechanics. These articles, which represent a snapshot of the cutting edge research currently conducted in this area, were contributed by leading groups in the field.

Various vascular components, including the endothelium and vascular smooth muscle cells, respond to the strains that they are exposed to. Their response potentially plays an important role in plaque progression. Understanding the impact of biomechanical stimuli on plaque development is essential for developing and optimizing imaging procedures and (pharmaceutical) interventions. When studying plaque mechanobiology, animal studies play a crucial role. This is the reason why the first contribution (Riou et al., 2014) is related to the biomechanical characterization of murine models and how they relate to human plaques. With appropriate animal models available, the hitherto largely unknown but important territory of strain related mechanobiological aspects of plaque development can be explored.

Mechanical stresses in plaques can potentially be used to assess plaque vulnerability. Accurate assessment of plaque stresses critically depends on the material properties of the plaque components. Akyildiz et al. (2014) show in a perspective review how plaque composition changes during plaque development and how composition might affect plaque properties and explain the wide variation of reported data in literature. The contribution by Chai et al. (2014) focuses on local mechanical properties of carotid plaques derived from compression experiments, using unconfined compression, micro-indentation or nano-indentation and a new method to analyze the local anisotropic mechanical properties of atherosclerotic plaques. The uniaxial mechanical testing approaches to characterize the mechanical properties of carotid, coronary or iliac plaques in vitro are outlined in the paper by Walsh et al. (2014). A more physiological way to assess plaque properties of carotid plaque samples excised from endarterectomy is described by Boekhoven et al. (2014). These contributions on macroscopic plaque properties clearly illustrate that well-controlled and documented experiments under physiologically relevant loading conditions are further needed to establish local non-linear and anisotropic plaque properties.

Although in vitro experiments are essential for deepening our understanding of the mechanical plaque properties, in vivo strain are important as a validation for the in vitro findings. Furthermore, blood pressure induced strain in atherosclerotic plaques can be associated with mechanical plaque composition, with the ultimate aim to classify stable and vulnerable atherosclerotic plaques. In vivo strain data can be obtained by several methodologies. Ultrasound based strain measurements are already used in various clinical applications including strain measurements in carotid plaques. A review and new developments in ultrasound strain imaging are discussed in the paper by Hansen et al. (2014). An alternative but less developed approach to assess carotid plaque strain involves MR-based strain imaging and is discussed by Nederveen et al. (2014). These papers show that these non-invasive imaging techniques show great potential but also require further development with respect to contrast enhancement and improvement of spatial and temporal resolution.

Most of the experimental and numerical studies on plaque biomechanics assume that the plaque components can be described with macroscopic continuum models. This continuum approach is the one followed most frequently, and especially when coupled to functional imaging might provide useful information and in essence is the only approach available when looking for clinical applications, when comparing plaque stresses to plaque strength. Whether stresses and strength can be determined using the macroscopic modeling approach is debatable, especially since plaque mechanics probably involve many (spatial) scales. The review article by Holzapfel et al. (2014) summarizes computational studies for different vessel types, and the modeling approaches that were followed in these studies, including studies on rupture mechanics. The contribution by Cardoso et al. (2014) applied multiscale computational analyses to evaluate the stress concentration generated by microcalcifications in plaques in order to shed further light on the issue of plaque rupture. Much is still unknown about the behavior of the individual plaque components and more theoretical, experimental and numerical studies are required to investigate whether we need to include multiscale plaque features for stress and strength analyses.

A subset of atherosclerotic plaques develops into a vulnerable phenotype. These vulnerable plaques are characterized by the presence of a large necrotic core, covered by a thin fibrous cap, often infiltrated by macrophages. Rupture of the cap is responsible for the majority of adverse cardiovascular events. Many studies focus on image-based determination of peak stress in the cap of atherosclerotic plaques. Teng et al. (2014) discuss the pathogenesis of plaque hemorrhage in carotid arteries, and its role in dictating plaque vulnerability. They also review imaging techniques, material properties of atherosclerotic tissues, and in particular, those obtained based on in vivo measurements and effect of plaque hemorrhage in modulating local biomechanics. Along the same line, Tang et al. (2014) illustrate findings in image-based models for human carotid and coronary plaques. The results of these manuscripts clearly illustrate that in a clinical setting, we need to deal with sparse and noisy data sets as input for our biomechanical models, and that this uncertainty needs to be accounted for when performing clinical studies.

Treatment of atherosclerotic plaques generally involves mechanical interventions. The interaction of the devices such as angioplasty balloons and stents with the atherosclerotic plaque is an important determinant of the efficacy of the procedure. The papers by Badel et al. (2014), Iannaccone et al. (2014) and Morlacchi et al. (2014) describe the effects of balloon expansion on arterial dissection, the arterial and plaque damage and lumen gain generated by the expansion of stents in different pathological carotid arteries, and the effects of plaque stiffness and cardiac wall movements on the fracture of coronary stents, respectively. The biophysics governing endovascular stenting, the simulations and statistical approaches that may help to bridge the gap between model finding and clinical predictions are reviewed by Kolandaivelu et al. (2014). If patient specific imaging data and more advanced material models can be included, these computational studies might provide an essential tool for the planning, prediction and optimization of interventional procedures.

Many important aspects of plaque biomechanics are discussed in this special issue, but it was not meant to cover all aspect. Notably, the role of blood flow induced shear stress, known to influence plaque initiation and progression, was not included. This special issue provides an overview of existing data and exiting new work in the area of plaque biomechanics, and we hope that you will enjoy this special issue. We would like to thank the editors for the opportunity to compose this special issue, and all the contributors for their collaborative efforts.

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