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On the Relevance of Accounting for Uid-Structure Interaction E Ects in the Numerical Studies of Type B Aortic Dissection

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ABSTRACT

This paper provides a brief review of advances in the numerical simulation of aortic dissection pathology. Even though majority of the numerical studies performed to-date rely on the assumption of rigid aortic walls and intimal ap, some recent studies reveal that including uid-solid interaction e ects is essential. The paper highlights that the uid-solid interaction studies are important not only for predicting the e ect of the solid deformation upon the haemodynamics in the lumina, but also for predicting the locations of highest stresses within the wall tissue. The limitations of the present approaches from the modeling point of view and from the practical points of view as well as possible ways of circumventing them are also outlined.

Abbreviations: AD: Aortic Dissection; FL: False Lumen; MRT: Magnetic Resonance Tomo-Gramy; ALE: Arbitrary Lagrangian Eulerian

Introduction: Aortic Dissection

Aortic pathologies are considered to be one of the most dangerous groups of cardiovascular disease due to their high morbidity and mortality (more than 50% in acute phase) [1]. Aortic Dissection (AD) is probably the most common injury of an aorta, 3 times more frequent than rupture of the aortic abdominal aneurysm. AD is burdened by a high mortality if not treated timely and adequately. The AD pathology is initiated by an intimal tear in the aortic wall. As the tear progresses, the tunica media of the aortic vessel splits leading to the formation of a secondary channel known as the "False Lumen" (FL). Once the anomaly is formed, the mortality rates are high. In case of aortic wall rupture, lethal outcome occurs nearly immediately due to severe internal bleeding. For type B ADs (i.e. those involving only the descending aorta) only 40 % of patients survive if untreated. In many cases an emergency surgical treatment is the only possible curative therapy. Nevertheless, surgical treatments are characterized by risk of vascular complications, bleeding or spinal ischemic cord injury [2]. If this occurs, subsequent medical management is impossible.

Moreover, if AD is asymptomatic and distal, it cannot be treated surgically and allows for pharmacological treatment only. In the long term, drug treatment is based on the use of beta blockers and ACE inhibitors [3], since the pressure of the subject must always be permanently controlled. The operative mortality rate in AD patients is low. Even though acute type B dissection is characterized by lower mortality rate that the acute type A (the one that involves the ascending aorta), type B persists even after correction. Type B aortic dissections have high mid/long term mortality primarily due to progressive aortic dilatation and subsequent rupture. In the clinical practice the prediction of the outcome in type B AD in the chronic phase is typically carried out on the basis of the maximum diameter of the entire aorta. Stanford criteria for surgical intervention include all kinds of patients (symptomatic and asymptomatic) with di erent AD types as well as false aneurysmal dilatation, for the cases where the pathological dimension is more than twice larger than the diameter of the contiguous\normal" aorta (more than 6 cm) [4]. Depending on the size the most adequate therapeutic treatment is chosen. Nevertheless, it was shown that the maximum aortic di-ameter is not a reliable indicator for predicting the pro-gression or rupture [5].

Experimental and Numerical Studies for Deter-Mining Risk Factors in Aortic Dissections

To date it is a generally accepted fact that knowing geometrical features of the patient's aorta (that can be easily obtained using Magnetic Resonance Tomo-gramy (MRT)) is insu cient for predicting the associated risks at the chronic stage. Such haemodyanmics factors as intra-luminal pressure, size and location of the tears in the intimal ap, magnitude wall shear stress as well as aortic wall properties appear to have an important impact upon the development of the diseases [6,7]. However, measuring or quantifying these parameters clinically is very challenging as it requires invasive techniques. For this reason, numerical simulations and ex vivo experiments can play an important role in studying the chronic AD progression in order to prevent lethal outcomes. Considerable amount of work has been dedicated to understanding the haemodynamics in the aortic dissection in ex vivo models [8,9], experimental phantoms [7,10-13] using numerical simulations of phantom models [14,15], using numerical sim-ulations considering AD geometries of real patients [6,16-18] and most recently using 4D phase-contrast MRI AD data [19,20].

Majority of the existing numerical simulations of AD considered uid dy-namics only, excluding the elastic e ects in the walls and the intimal ap (e.g. [14-16]). The models typically performed well when validated using the data of in vitro phantom experiments, but the materials (silicon/latex) used for aortic walls and the ap in the in vitro models are considerably stier than the actual aortic tissue. In [21] the comparison of the computational model results with the patient-specic studies demonstrated that rigid wall models over-predict the pulsatility of both pressure and ow wave-forms, even if the mean ow is not greatly an ected. The error may be as high as 50 %, however in type B chronic ADs the di erences may be smaller due to the fact that the aortic wall and the septum are generally sti er than in other AD types. Even for the cases where uid ow is not greatly a ected by the solid defor-mations, FSI models may have a significant importance. In particular, numerical models based on the assumption of rigid walls are incapable of predicting stress distribution within the ap and the aortic wall, which is necessary for identifying the regions potentially prone to rupture.

Fully coupled FSI simulations based on partitioned Arbitrary Lagrangian Eulerian (ALE) approach was performed considering simpli ed AD geometry in [22]. Von Mises wall stress was estimated. The results of this study showd that peak wall stress and maximum shear stress are highest in the media layer. In [23] the evolution of principal stresses at several locations of the intimal ap was com-puted using a monolithic ALE FSI model and it was shown that the stress evolution pro le closely resembles that of the uid pressure in the lumina, while the maximum stress values are 15 % higher than that of the ow pressure. Moreover, high frequency solid oscillations were identified at some locations [24]. In [18] partitioned FSI sim-ulation of acute aortic dissection were performed using ABAQUS software and compared against an experiment made on a fraction of porcine aorta connected to an electronically actuated pulsatile ow pump. The geometry of the aorta used in the simulation was greatly simplied. The analysis concentrated on ow velocities in true and false lumina as well as the stresses in the ap. However, porcine aorta strongly di er from the human aorta in terms of wall thickness and material properties. Partitioned FSI simulations using ANSYS of aortic dissection based on a sample patient case were performed in [6].

The study obtained predictions of wall shear stress significant-ly different from those obtained by the rigid wall model. Moreover, it was shown that when performing the studies using the material properties of the real human aorta, the e ects of the deformation of the walls and intimal ap also stop being negligible even in type B dissections. Slight rotations of the tears may considerably change the location of the impact of the jets originating from the tears. Ac-curate prediction of the FL outer wall location exposed to the jet im-pact may indicate the areas exposed to enhanced danger of rupture.

Limitations of the Present Approaches

The use of computational modeling technology opened a new path for predicting the behavior of a complex mechanical system involving blood ow in the dissected aorta. Several recent studies have shown that uid-solid interaction simulations are mandatory for obtaining reliable predictions. They provide estimation of the wall stress distributions that cannot be obtained when applying the rigid-body models. More-over, even though the works performed considering the properties of in vitro phantoms confirmed that the solid deformations are negligible in terms of their e ect upon the uid ow, it was discovered that when performing simulations using the material properties of a true human aorta, the blood ow indeed becomes an ected by the solid deformations.

This calls for major e orts devoted to numerical simulations using the data corresponding to human patients. The latest FSI technology existing in the modeling community is indeed mature enough so as to perform the reliable AD simulations (which is shown by successful validation of several computational models by means of comparison with in vitro experiments). Two factors still constitute a significant bottleneck for extensive application of FSI models to AD studies in clinical practice. First is the high computational cost of the FSI simulations, particularly when using commercial software. Low density of aorta makes the simulations using conventional FSI models very challenging due to the "added mass e ect", which manifests when the density ratio between the uid and the solid is close to 1 [25,26]. This leads to slow convergence rates of standard partitioned FSI solvers (typically implemented in

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the commercial computational uid dynamics software) if no special remedies, such as e.g. dynamic under-relaxation are implemented [27]. Therefore, application of front-edge FSI models available in many Open Source code (e.g. OpenFOAM [28] or KRATOS [29]) for the problem at hand should be encouraged.

Monolithic solvers, that do not su er added mass e ect (such as e.g. the ones proposed for bio-mechanics problems in [23], [30]) equipped with acceleration strategies [31] or/and powerful iterative solvers suitable for solution of poorly condition linear systems [32] appear to be promising for the problem at hand. Moreover, open source codes permit implementing user-defined acceleration techniques, linear solver libraries that can lead to important improvement in computational times. Second problem originates from the fact that computational model developers have a very limited exposure to the true test cases taken from the medical practice, and, as it is put in evidence in the present work, commonly perform their simulations on simplified geometries, which strongly reduce practical relevance of their simulation results. Practically all studies performed to date have majorly qualitative relevance and the corresponding results do not have direct impact on the clinical practice. Three requirements must be met for obtaining reliable predictions of practical importance:

a) Availability of reliable patient-specific clinical data (including MRT images, material properties and haemodyanmics boundary conditions).

b) Availability of stable FSI models tailored specially for the AD studies.

c) Possibility of creating databases with the case studies available to the healthcare community.

Therefore, only bringing together the computational model developers and the healthcare professionals may result in a true breakthrough in virtual prediction of the risk in the development of chronic aortic dissections. Consequently, better understanding will enable establishing better strategies for the treatment of patients with chronic type B ADs in the long-term perspective via determination of areas of potential aortic augmentation.

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