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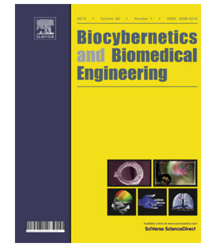

Original Research Article

Geometric verification of the validity of Finite Element Method analysis of Abdominal Aortic Aneurysms based on Magnetic Resonance Imaging

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ABSTRACT

The currently used criterion of maximum transverse diameter for the Abdominal Aortic Aneurysm treatment has some limitations. Therefore, studies aiming at creating an individualized, therapeutic strategies are being conducted. Those include biomechanical assessment of rupture risk of an aneurysm based on the Finite Element Analysis of the geometric models of the aneurysm.

The usual approach is to use the results of the computed tomography imaging to build a three-dimensional model of the aneurysm. The FEA is then performed and the resulting stress is analyzed to estimate the risk of rupture. Although such an approach brings significant improvements over the traditional maximum diameter method, it is difficult to ensure the validity of the assumptions (e.g. the material model) made.

This paper presents a method to evaluate the correctness of such a modeling approach. The emergence of gated Magnetic Resonance Imaging (MRI) provides an opportunity to register aneurysm in both the systolic and diastolic phase of cardiac cycle. The corresponding geometric models are built and the results of the FEA applied to the diastolic model are compared with the actual deformation of the aneurysm observed in the patient's body – the systolic model. As a result, it is possible to verify whether the individualized diagnostic approach applied to a specific patient was correct.

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The geometry of the reference data and the analyzed models were compared using the Differential Surface Area Method to obtain geometry error for each case. The average geometry error equals 1.65%. In the best case the error amounts to 1.04%, in the worst to 3.00%.

The obtained results are satisfactory and provide significant evidence that the Finite Element Analysis is a reliable method and can be potentially used for individualized diagnostics and treatment.

1. Introduction

Abdominal aortic aneurysm (AAA) is the most common true arterial aneurysm. The designation ''true'' means that all three layers of the aorta are degenerated, as opposed to the pseudoaneurysms, which are results of blood leaking through the inner layers of the aorta. A diameter of infrarenal abdominal aorta of 3.0 cm or more is the most accepted definition of AAA [1]. Risk factors for AAA include current or past smoking, advanced age, gender (male), atherosclerosis, hypertension, family history of AAA and other large arteries aneurysms.

AAA rupture is the tenth leading cause of death in men above 65 years with mortality ranges from 70% to 90% [2]. Although the most widely accepted indication for surgical repair is the maximal transverse diameter exceeding 5.5 cm, according to literature, 10–24% of ruptured aneurysms were significantly smaller [3,4]. Thus, biomechanical modeling of AAA based on Finite Element Analysis (FEM) as the patient-specific approach to accurate rupture risk estimation has been extensively explored.

Different modalities of imaging have been used for diagnostics of AAA. The ultrasound (US) measurements have been used mostly for initial screening and detection of AAA [5]. However, the usefulness of US for precise reconstruction of the AAA geometry is limited, as the imaging depends on the manual motions of the operator's hand and the results may be inaccurate for example in case of obese or bloated patients [6]. US was successfully used in [7], where it was applied to measuring the hemodynamics in the affected segment of the aorta, however the geometric model was acquired using CT scanning. The only US method allowing reconstruction of geometry is intravascular ultrasound (IVUS), which is an invasive technique performed during the coronary angiography procedure [8]. Recently, the 3D ultrasound speckle tracking (UST) was used to register the geometry of AAA, which then served as a basis for a membrane FEA model, however this approach still suffers from the limitations of AAA imaging mentioned earlier [9]. Moreover, disadvantage of UST is poor temporal resolution and overall image quality [10].

Most of the research on modeling aneurysms is based on computed tomography (CT) or computed tomography angiography (CTA) scans as those are routine modalities in detailed diagnostic process. Magnetic Resonance Imaging (MRI) technique is less common due to lower resolution [11–14] and higher cost of an examination. The choice of image acquisition method determines some aspects of aneurysm modeling. It has been proven that thickness of the vessel wall is not uniform in the whole aneurysm [15–17]. Extraction of an accurate wall thickness from CT/CTA scans is currently impossible, therefore homogeneous thickness has to be assumed [18–21]. In contrast, the high quality MR examination provides information on wall geometrical parameters [11], hence it may result in creating more adequate vessel model. In recent studies incorporation of intraluminal thrombus (ILT) into aneurysm model is examined [22,23], however other pathological wall inclusions, as calcification or local inflammation, are not commonly embodied. The few papers which cover the issue of detailed composition of AAA model benefit from measurements taken with both MRI and CT for each patient in order to overcome all of the acquisition-specific limitations [24,25]. There is a wide range of constitutive descriptions of the arterial wall [26–28], ILT [29–32] and calcifications [33–35]. It is worth mentioning that the aforementioned properties are population mean values as patient-specific parameters are difficult to obtain noninvasively. The traditional approach of defining loads affecting on aneurysm model is to apply static, uniform systolic blood pressure [36–38] or mean arterial pressure (MAP) [39,40]. Currently, the computational fluid dynamics (CFD) or fluid–structure interaction (FSI) modeling is being widely developed [41–43], as they employ the impact of hemodynamics on wall stress [44].

Considering the wide range of mechanical parameters that could have impact on the FEA results, the matter of verification of AAA models arises. There is no extensive research on this subject, however few different approaches are proposed. The most common idea is to perform experiments on phantoms of AAA and compare the outcome to the results of FEA [21,45]. The main limitation of this method is the mechanical behavior of phantom material which is not identical with aneurysm wall. More direct validation procedure is presented in [46], where the estimated rupture location is confronted with the actual location of blood extravasation. The major drawback of such study is of ethical nature and it may be performed only if there are contradictions to surgical intervention or as a patient decision. The last validation method is based on performing the FEA of given aneurysms by several operators and repeating the whole procedure couple of times in assumed time intervals. The estimated consistency of the results is then used to quantify of modeling accuracy [47]. This approach can be used to verify precision of the AAA model preparation but is insufficient to evaluate accuracy of mechanical parameters selection.