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Dynamic simulation and Doppler Ultrasonography validation of blood flow behavior in Abdominal Aortic Aneurysm

Cristian C. Botar [a], Árpád Á. Tóth [b,*], Olivera R. Klisurić [b], Dijana D. Nićiforović [c,d], Viktorija A. Vučaj Ćirilović [c,d], Viktor E. Till [c,d]

[a] "Babes-Bolyai" University, Department of Chemical Engineering, Cluj-Napoca, Romania
[b] University of Novi Sad, Faculty of Sciences, Department of Physics, Novi Sad, Serbia
[c] Clinical Centre of Vojvodina, Centre of Radiology, Novi Sad, Serbia
[d] University of Novi Sad, Medical Faculty, Novi Sad, Serbia

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ABSTRACT

Criteria for rupture prediction of Abdominal Aortic Aneurysm (AAA) are based only on the diameter of AAA. This method does not consider complex hemodynamic forces exerted on AAA wall. The methodology used in our study combines Computer-Aided Design (CAD) with Computational Fluid Dynamics (CFD). Three-dimensional vascular structures reconstructions were based on Computed Tomography (CT) images and CAD. CFD theory was used for mathematical modeling and simulations. In this way, dynamic behavior of blood flow in bounded three-dimensional space was described. Doppler Ultrasonography (US) was used for model results validation. All simulations were based on medical investigation of 4 patients (male older than 65 years) with diagnosed AAA. Good correspondence between computed velocities in AAA and measured values with Doppler US (Patient 1 0.60 $m \cdot s^{-1}$ versus 0.61 $m \cdot s^{-1}$, Patient 2 0.80 $m \cdot s^{-1}$ versus 0.80 $m \cdot s^{-1}$, Patient 3 0.75 $m \cdot s^{-1}$ versus 0.78 $m \cdot s^{-1}$, Patient 4 0.50 $m \cdot s^{-1}$ versus 0.49 $m \cdot s^{-1}$) was noticed. The good agreement between measured and simulated velocities validates our methodology and the other data available from simulations (eg. von Misses stress) could be used to provide useful information about the possibility of AAA rupture.

1. Introduction

The paradigms of modern medical care are constantly changing and are converging toward totally noninvasive methods for supporting diagnosis and therapeutic decisions. With respect to cardiovascular pathology, this shift in the medical care has been enabled by the continuous development of numerical tools capable of simulating blood flow in complex geometries and to reproduce real systems and accurately evaluate their behavior. Clinically, there is interest in the possibility of using such numerical tools, which should be relatively user-friendly to support diagnosis and therapeutic decisions, through exploiting their ability to reproduce complex phenomena in dynamic 3D virtual space.

In particular, the intersection between medical imaging methods and computational mathematical modeling may provide relevant solutions to real problems for various hypothetical scenarios, in a very short time and in a totally noninvasive manner for the patient.

This methodology can be successfully applied to study the hemodynamic and mechanical behavior of Abdominal Aortic Aneurysms (AAA) and to assess the consequences of the presence and evolution of this condition.

Physiologically, AAA is associated with dilatation of the abdominal aorta near the bifurcation of common iliac arteries. The appearance of this dilatation has the effect of weakening the resistance of the arterial wall and promotes the emergence of vascular ruptures with fatal effects to the patient [1,2]. In addition to the possibility of vascular rupture AAA is associated with various cardiovascular diseases, especially myocardial infarction and stroke [3].

In terms of incidence, AAA is present in both men and women (more common among men) and AAA incidence in both sexes has seen a continuous upward trend [4,5] which makes this disease the subject of increasing attention. In addition, the incidence of AAA is directly proportional to the age of the population [1].

Unfortunately, diagnosis of AAA is problematic, since it often occurs as an asymptomatic condition. Because of this, AAA is usually found only in the advanced stages of development, and is generally identified only after a routine or unrelated medical exam

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* Corresponding author at: Trg Dositeja Obradovića 4, 21000 Novi Sad, Serbia.
E-mail address: arpad.toth@df.uns.ac.rs (Á.Á. Tóth).

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[6–8]. Evolution of AAA is in most cases progressive, and a lack of prognostic indicators or the application of inappropriate treatment can lead to patient death. In advanced stages, AAA requires surgery. However, in the majority of cases, even surgery is not a 100% life-saving solution; arterial segments that were subjected to surgery show an increased chance of relapse, or even rupture [9].

Moreover, enabling patient-specific analysis of blood flow could offer a more relevant representation of hemodynamic than that provided by clinical [10–13] or experimental models. This type of patient-specific analysis could be used not only to assess the risk of rupture associated with AAA, but also to plan surgery or to predict treatment outcomes. A major strength of these approaches, when supported by computational means, is their high level of reproducibility [14]; as supported by previous studies conducted on brain aneurysms [15]. Thus, this type of investigative methodology may enable the development of powerful new tools for improving medical diagnosis, treatment and surgical planning.

A range of models have been previously reported to simulate the complex dynamics of blood flow in AAA, both for flow and the mechanical behavior of the arterial wall. Beginning with models that assumed a rigid arterial wall [16–19] and continuing with models that considered the elastic nature of the arterial wall [20], researchers tried to predict several essential characteristics of blood flow, such as: velocity, flow pattern distributions and the propagation of pressure waves. However, no generally applicable algorithms that can accurately reproduce the dynamic behavior of blood flow have been established. Therefore, development of a deeper understanding of the influences which contribute to the emergence of AAA, such as the non-Newtonian characteristics of blood, the complex interactions between fluid and blood vessel walls, or the influence of organ movement around the aneurysm, requires a complex analysis of blood dynamics and solid mechanics in the AAA [21–24].

With respect to AAA, numerous studies have been conducted to correlate hemodynamic with the evolution of aneurysm size and to estimate the possibility of rupture [25–30]. However, presently there is a need to consider blood vessel elasticity and the interaction between the fluid and the vessel wall, and the modeling assumption of a rigid wall is no longer acceptable.

In fact, despite the progress made to date, there are many problems remaining, not only with respect to the way in which vessel elasticity is introduced in current mathematical models, or in which the acquisition of realistic vascular geometries and modeling flow phenomena and the flow/vessels wall mechanical interaction is conducted, but also in terms of validation of computational methods against experimental or clinical data. In this regard there have been few *in vivo* studies [30], but there are many papers in which fluid/vascular wall interactions have been simulated in artificial replicas of abdominal arteries and AAA [31,32]. Therefore, considering all of the above, our research focuses on evaluation of a computational method to non-invasively investigate the complex dynamic behavior of blood flow in AAA and, at the same time, validation of our proposed methodology and mathematical model using clinical data provided by Doppler ultrasound measurements. Our intention was to develop a method which in the future might help contribute in terms of evaluation, prediction and/or early diagnosis of AAA, as well as for optimization of therapeutic decisions and surgical planning.

2. Materials and methods

This paper treats three main issues: 1) Abdominal Aortic Aneurysm geometry acquisition; 2) blood flow modeling and simulation; and 3) simulation results validation against clinical data.

2.1. Abdominal Aortic Aneurysm geometry acquisition

Geometric 3D reconstruction and modeling based on medical imaging techniques is the first and most important step in simulating blood flow in complex real systems. In our case we used the CT images which in a relative short time offer high quality images. Even so, geometry reconstruction based on them is still a tedious task; but highly trained professionals can provide the 3D vessel reconstructed structures for preprocessing operations, within several hours. Therefore, today custom calculations of blood flow dynamics, specific to each patient, are no more a question of time and could be successfully used in mathematical modeling and simulation procedures for support in diagnostic and medical decision. Patient specific geometry reconstructions are imperative because the anatomy of any vascular structures vary significantly from one patient to another, both under normal physiological and pathological conditions.

To date, two basic techniques for 3D reconstruction of vascular patterns have been developed. The first uses a series of outlines of vascular elements, that are captured by medical imaging techniques in 2D cross-sectional images, and extended along the blood vessel path line to obtain vascular surfaces [33,34] or volumes [19]; and the second is based on triangular or polygonal modeling, where the 3D segmentation is applied automatically and triangulated into a single surface [35,36]. Although the second method is much faster than the first one, it has the disadvantage of being more difficult to edit: it can be applied only if the images taken by imaging techniques are of very high quality, and when it is applied to rebuild large geometries. In addition, geometric structures made by this technique cannot be changed after-the-fact, to be used for studying potential changes arising from developments in the size of the AAA, or when surgery is planned. Therefore, in the present study we apply the first method discussed above, because it is more simple and versatile, it allows an exact reconstruction of the vascular profile, even for low contrast images, and it emphasizes the details of any type of vascular structure [19], in particular those of small size.

In order to model blood flow, and for results validation purposes, the present study includes 4 patients diagnosed with AAA. All patients were elderly males older than 65 years, and all have been clinically investigated with Computer Tomography (CT – Siemens Somatom Sensation 64) and US Doppler. The prescribed parameters for CT image acquisition are presented in Table 1.

The technical characteristics of the US Doppler machine used in this study are: Ultrasound Logiq 7 BT 06 machine, with a Convex probe 4C, and the following B mode settings (Freq 5.0 MHz, AO = 100%, Gn 74, DR 81), Doppler color settings (Freq 2 MHz, PRF 0.5 kHz, Gn 14, WF 81 kHz) and Pulse Doppler settings (SVD – 6.2 cm, GN 14, PRF 1.6 kHz, DR 36, WF 81 Hz). US Doppler velocity measurement uncertainty was 6%.

A CT was used to obtain 2D cross-sectional images, which provided the basis for 3D reconstruction of the AAA geometry and its adjacent arterial segments. For this purpose we used dedicated commercial Computer Aided Design (CAD) software Solid Edge V20, which allowed us to reconstruct, specifically for each patient, the real geometry of the AAA. The following parts of the abdominal arterial system were designed: Abdominal Aorta (with Aneurysm), Renal Arteries, Iliac Arteries, and in some cases Internal Iliac Arteries.

The maximum diameter obtained from US Doppler investigations was the following: Patient 1 (65 years old) – 4.2 cm, Patient 2 (76 years old) – 5.69 cm, Patient 3 (78 years old) – 5.6 cm, Patient 4 (69 years old) – 5.4 cm.

The steps followed in AAA geometry reconstruction are illustrated by the images shown in Fig. 1. The first step consisted of