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Nonlinear resonances of an idealized saccular aneurysm

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ABSTRACT

This paper investigates the occurrence of dynamic instabilities in idealized intracranial saccular aneurysms subjected to pulsatile blood flow and surrounded by cerebral spinal fluid. The problem has been approached extending the original 2D model of Shah and Humphrey (1999) to a 3D framework. The justification for using a 3D formulation arises from the works of Suzuki and Ohara (1978), MacDonald et al. (2000) and Costalat et al. (2011) who showed experimental evidences of intracranial aneurysms with a ratio between wall thickness and inner radius larger that 0.1. Two different material models have been used to describe the mechanical behaviour of the aneurysmal wall: Neo-Hookean and Mooney–Rivlin. To the authors' knowledge, for the first time in literature, the dynamic response of the aneurysm has been analysed using complete nonlinear resonance diagrams that have been obtained from a numerical procedure specifically designed for that purpose. Our numerical results show that, for a wide range of wall thicknesses and both constitutive models considered, the saccular aneurysms are dynamically stable within the range of frequencies associated to the normal heart rates, which confirms previous results of Shah and Humphrey (1999). On the other hand, our results also show that the geometric and material nonlinearities of the problem could bring closer than expected the resonance frequencies of the aneurysm to the frequencies of the pulsatile blood flow.

1. Introduction

The question of whether mechanical instabilities, both static and dynamic, may cause the enlargement and rupture of saccular aneurysms has been debated by the scientific community during the last 40 years. Several researchers, such as Akkas (1990) and Austin, Schievink, and Williams (1989), pointed out that the existence of limit point instabilities (i.e. mathematical bifurcations in the quasi-static response of the aneurysm) could be a reason for the growth and rupture of this type of lesions. Alternatively, other authors like Jain (1963), Sekhar and Heros (1981) and Sekhart, Sclabassi, Sun, Blue, and Wasserman (1988) suggested that the pulsatile blood flow could excite the natural frequency of the aneurysm making it dynamically unstable. This hypothesis was supported by the results of Simkins and Stehbens (1973) and Hung and Botwin (1975), who studied the elastodynamics of berry aneurysms and showed that the natural frequency of these type of lesions may lie within the range of bruit frequencies that commonly accompany aneurysms. However, despite the nonlinear stress-strain response exhibited by the aneurysmal wall over finite strains, these authors used in their analysis the classical shell membrane theory, which assumes infinitesimal strains and linear material behaviour. Furthermore, they ignored the

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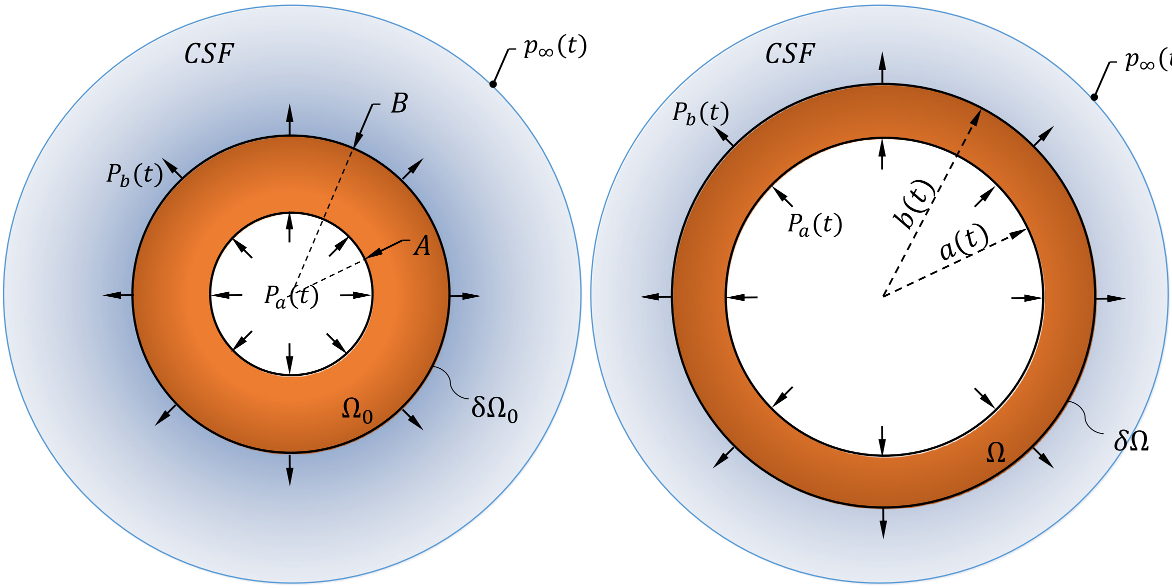

Fig. 1. Schematic representation of an idealized saccular (spherical) aneurysm surrounded by cerebral spinal fluid and subjected to radially symmetric pulsating blood pressure. (a) Reference and (b) deformed configurations.

contribution of the Cerebral Spinal Fluid (CSF) surrounding the lesion. Thus, the idea that resonances may cause the rupture of intracranial aneurysms has been gradually losing support within the scientific community.

Shah and Humphrey (1999) and David and Humphrey (2003) studied the nonlinear elastodynamics of a sub-class of spherical aneurysms subjected to pulsatile blood pressure and surrounded by CSF. The aneurysmal wall was modelled using a Fung-type pseudostrain-energy function which included strain rate dependence. These works brought to light that both surrounding fluid and material viscosity help to increase the dynamic stability of the aneurysm. Shortly after, Haslach and Humphrey (2004) provided further insights into the effect of the mechanical behaviour of the aneurysmal wall on the dynamic response of the lesion. Through the comparison of various strain energy functions, the authors pointed out the great sensitivity of the dynamic behaviour of the aneurysm to the constitutive model used to describe the aneurysmal wall. In particular, they stressed the fact that it is essential for the (correct) analysis of the dynamic stability of aneurysms to use constitutive models specifically formulated and calibrated for the aneurysmal wall. It was shown that the opposite may give rise to misleading results which predict dynamic instabilities that there are not present in actual tissue.

In this research we revisit the works of Humphrey and co-workers (David & Humphrey, 2003; Haslach & Humphrey, 2004; Shah & Humphrey, 1999) and extend their 2D elastodynamics model to a 3D framework[1] in order to study the dynamic response of idealized saccular aneurysms. While many aneurysmal lesions show small wall thickness and thus can be modelled relying on the membrane hypothesis, the justification for using a 3D formulation arises from the works of Suzuki and Ohara (1978), MacDonald, Finaly, and Canham (2000) and Costalat et al. (2011) who obtained experimental evidences of intracranial aneurysms with a ratio between wall thickness and inner radius larger that 0.1, leading to non-negligible radial stresses through the aneurysmal wall. Another original feature of our research is that the we have obtained, for the first time in literature, to the authors' knowledge, the complete nonlinear resonance diagrams that characterize the dynamic response of the aneurysm as a function of the pulsatile blood flow. A Mooney–Rivlin type constitutive model, calibrated by Costalat et al. (2011) using experimental data obtained from 16 different intracranial aneurysms tested under physiological conditions, has been used to describe the mechanical behaviour of the aneurysmal wall. The results are systematically compared with those obtained from a simple Neo-Hookean model widely applied to characterize the behaviour rubber-like materials. This research shows that, for any of the constitutive models used and irrespectively of the thickness of the aneurysmal wall, the resonance frequencies of the aneurysm do not lie within the range of frequencies associated to the normal heart rates, which in turn seems to confirm the earlier findings of Shah and Humphrey (1999).

2. Problem formulation

In this section we formulate the problem of an idealized intracranial saccular (spherical) aneurysm surrounded by CSF and subjected to pulsating, and radially symmetric, blood pressure (see Fig. 1). The original contribution is to extend the 2D

[1] For which we have followed the pioneering work of Knowles (1962).