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Wall expansion assessment of an intracranial aneurysm model by a 3D Digital Image Correlation System

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ABSTRACT

Intracranial aneurysm is a local dilatation of an intracranial artery with high risk of rupture and death. Although it is generally accepted that the weakening of the arterial wall is the main cause for the rupture of an aneurysm, it still no consensus about the reasons for its creation, expansion and rupture. In particular, what is the role played by the blood flow in these phenomena. In this way, the aim of this work is the *in vitro* mechanical assessment of the wall expansion, namely the displacements, deformations and strains occurring in a saccular intracranial aneurysm model, when subjected to different flow rates. To obtain new insights into the mechanisms involved in the aneurysm rupture, a 3D-Vic™ Digital Image Correlation System was used and validated with a finite element analysis. The wall expansion results have revealed that the displacements, deformations and principal strains are directly related to the internal pressure caused by the fluid on the wall of the aneurism. These findings were especially observed in the weakened areas of the aneurysm model, where the wall was thinner. Furthermore, the technique used in this study has shown to be a potential method to validate numerical simulations of aneurysms, allowing the future performance of more complex and realistic haemodynamic studies.

1. Introduction

Intracranial aneurysm (IA), is an intracranial artery dilation with a saccular or berry form [1,2] that affects 2–6% of the general population [3,4,2], and causes almost 85% of the subarachnoid haemorrhages (also known as SAH) [3]. Although the general consensus in the scientific community that the main cause for the IA creation, is the weakening of the arterial wall [3,4], the biological, physiological and biomechanical features behind that wall weakening are still unknown [5]. Nevertheless, it is recognized that the more probable causes for this phenomenon, are mainly the acquired lesions caused by congenital defects, atherosclerotic changes, trauma or infectious emboli [3,6,7,4]. It is also notice that persons with some risk factors (such as hypertension, smoking and heavy alcohol consumption, increasing age, female sex and familiar occurrence) are more likely to develop IAs [3,2]. Moreover, the internal pressure of blood flow may also have an important effect in the rupture of the aneurysm, which represents a high risk of death. Thus, a better understanding of the relationship between the pathophysiological aspects of an aneurysm, the arterial geometry and local haemodynamics, are still needed to improve the clinical understanding of the aneurysm

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growth, regrowth after a treatment or even to improve the existent endovascular treatments [5].

To achieve these new insights, several mathematical and experimental studies have been made in simple geometries over the past years [8–13], investigating the haemodynamic behaviour of the blood cells in arteries. Nevertheless, realistic haemodynamic studies concerning the complex mechanical wall expansion phenomena in aneurysm's models, are still lacking.

In haemodynamic studies of aneurysms, it is crucial to perform accurate measurements of displacements and strain fields in the global deformation of their walls under the blood flow pressure [14,15,5]. For this purpose, the experimental full-field optical techniques, which can be classified as interferometric, photoelastic and digital image correlation (DIC) [5], are promising approaches to understand the mechanical behaviour of the aneurysms [16–18]. In brief, the *interferometric techniques* are mainly based on the interferometry phenomenon of light using a coherent light (laser), e.g., Holography, the Moiré Interferometry and the Speckle [19]. The *photoelastic methods* use the optical properties of certain materials, i.e. birefringence [20], and the *DIC techniques*, is based on the comparison of two acquired images using correlative methods and high-speed digital cameras [21,22].

Recently, Pinho et al. [5] have developed a system able to perform an experimental study of the displacement field of an *in vitro* intracranial aneurysm model, fabricated in polydimethylsiloxane (PDMS) and using an Electronic Speckle Pattern Interferometry (ESPI) technique. The results have shown that when high spatial resolution is used, the ESPI technique performs a good correlation of the displacements and allows the extraction of information for the applied deformation. However, this technique also has revealed some drawbacks related to the high sensitivity of this technique for big displacements, which can promote an incorrect pattern generated by the laser beam.

Recently, the DIC technique have shown to be less sensitive for small displacements than ESPI technique [21,22] and therefore, more suitable to study small displacements happening in *in vitro* models, such as intracranial aneurysms models. In this way, this work aims to gain new insights into haemodynamic phenomena related to the wall expansion of a mimicking IA model when subjected to different flow rates by using a 3D DIC technique (3D-DIC™ DIC system), which to the best of our knowledge, this combination has never been reported previously. To achieve this purpose, an improved polymeric 3D aneurysm model, based on clinical data for a common saccular IA, was fabricated in real scale using an elastomeric polymer with biocompatible, hyper-elastic and irregular wall thickness features, similarly to *in vivo* blood vessels walls. Thus, the displacements, deformations and strains that occurred in the mimicking wall of the 3D aneurysm model, where assessed and related to the fluid pressure caused by the flow rate increment. Moreover, the used 3D DIC technique was prior validated, especially concerning the out-of-plane analysis, by comparing experimental results of a simple and controlled mechanical test with finite element analysis (FEA).

2. Materials and methods

2.1. Fabrication of the aneurysm model

The IA model was fabricated using a 3D printer combined with a soft lithography technique, as previously reported by Pinho et al. [5], using a biocompatible and hyper-elastic polymer, polydimethylsiloxane (PDMS), which mimics the biomechanical behaviour of the blood vessels system [23,24].

The geometry and dimensions of the aneurysm model were based on clinical data for a common saccular IA and drawn in the Solidworks® CAD software, as shown in Fig. 1(a). The mould was fabricated in Acrylonitrile Butadiene Styrene (ABS) material using a Solidoodle® 3D Printer (New York, USA) and treated with acetone vapour, in order to create a smooth surface on the model. Pre-polymer PDMS and its curing agent (Sylgard 184, Dow Corning Corporation) were mixed in a proportion of 10:1 to form the PDMS elastomer. After the complete cure (42 h at room temperature) of the PDMS, the mould was placed into an oven at 80 °C during 30 min. Finally, the mould was cooled down, cut and the inlet and outlet of the channel were connected, resulting in the PDMS aneurysm model represented in Fig. 1(b).

2.2. Experimental set-up

2.2.1. Principle of the Vic-3D DIC System

The experimental method used in this work was the Vic-3D™ Digital Image Correlation System (Correlated Solutions, South Carolina, USA). The DIC principle is based in the generation of a random speckle pattern on the observed surface of the sample, which is captured either with a single fixed camera – for a two-dimensional (2D) images –, or with two charged couple device (CCD) cameras – for a three-dimensional (3D) images based on the principle of the binocular stereovision [25]. This latter 3D DIC technique, is a well known methodology and widely accepted for biomechanical tests, especially regarding the measurements of the full field displacements, deformations and local strains of both simple and complex 3D geometries. The main advantages of this technique are the following: (i) simple experimental set-up and preparation requirements; (ii) low environmental sensitivity; (iii) easier and automatic processing; (iv) non-contacting measurement requirements; and (v) good spatial resolution [26,27,22,28].

In this work the Vic-3D™ DIC was used with a stereovision system of two high-resolution cameras (Gras-20S4M-C, Pentax tv lens 75 mm; 1624 × 1224 pixels at 30 FPS; 2.0 MP; Sony ICX274 CCD; Global Shutter; Mono; C-mount) that have allowed the 3D track of grey value patterns from small neighbourhoods, called as subsets. To achieve the effective correlation of the Vic-3D™ DIC System, two main parameters were set prior to the beginning of the experimental assays, namely (i) the *speckle pattern of the samples*, which has to be a non-repetitive, isotropic and with high contrast; and (ii) the *CCD cameras calibration*, which has allowed the determination of the camera positions relative