Lecture Notes in Mechanical Engineering

José Machado · Filomena Soares · Justyna Trojanowska · Erika Ottaviano · Petr Valášek · Mallikarjuna Reddy D. · Eduardo André Perondi · Yevheniia Basova *Editors*

Innovations in Mechanical Engineering II

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Preface

This volume of Lecture Notes in Mechanical Engineering gathers selected papers presented at the Second International Scientific Conference (ICIE'2022), held in Guimarães, Portugal, on 28–30 June 2022. The conference was organized by the School of Engineering of University of Minho, throughout MEtRICs and Algoritmi Research Centres.

The aim of the conference was to present the latest engineering achievements and innovations and to provide a chance for exchanging views and opinions concerning the creation of added value for the industry and for the society. The main conference topics include (but are not limited to):

- Innovation
- Industrial Engineering
- Mechanical Engineering
- Mechatronics Engineering
- Systems and Applications
- Societal Challenges
- Industrial Property

The organizers received 139 contributions from 16 countries around the world.

After a thorough peer-review process, the committee accepted 81 papers written by 335 authors from 15 countries for the conference proceedings (acceptance rate of 58%), which were organized in three volumes of the Springer Lecture Notes in Mechanical Engineering.

This volume, with the title "Innovations in Mechanical Engineering II", is specifically spanning from advanced materials and composites, optimization of manufacturing and production processes and converging issues and technologies in additive manufacturing and Industry 4.0. It covers applications in the transport and automotive, and medical and education sector, among others. Last but not least, it analyses important issues proposing a good balance of theoretical and practical aspects. This book consists of 30 chapters, prepared by 146 authors from ten countries.

Extended versions of selected best papers from the conference will be published in the following journals: Sensors, Applied Sciences, Machines, Management and Production Engineering Review, International Journal of Mechatronics and Applied Mechanics, SN Applied Sciences, Dirección y Organización, and Smart Science, Business Systems Research and International Journal of E-Services and Mobile Applications.

A special thank to the members of the International Scientific Committee for their hard work during the review process.

We acknowledge all that contributed to the staging of ICIE'2022: authors, committees and sponsors. Their involvement and hard work were crucial to the success of ICIE'2022.

June 2022

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Contents

Flow Visualizations in a PDMS Cerebral Aneurysm Biomodel

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Abstract. Cerebral aneurysm is an abnormal dilatation of the blood vessel which affects a high percentage of the worldwide population. One way to investigate this pathology is using *in vivo* techniques, but these types of experiments have a high cost and low reproducibility. Thus, to understand the local hemodynamics of brain aneurysms, it is imperative to manufacture *in vitro* models that simulate real brain aneurysms. These biomodels are suitable for experimental testing, as well as for evaluating and validating computational models. In this work, was manufactured a biomodel of a cerebral aneurysm made by polydimethylsiloxane (PDMS), combining rapid prototyping technology with a PDMS gravity casting process. Experimental flow visualizations were performed at different flow rates. The flow visualizations results have shown that there is a transition from laminar to turbulent flow for a flow rate near 6 ml/min. The proposed PDMS biomodels have shown the ability to perform flow visualizations and have the potential to help the development and validation of computational models.

Keywords: Cerebral aneurysm · In vitro tests · PDMS flow biomodels

1 Introduction

A cerebral aneurysm is an abnormal dilatation of a blood vessel [1]. Its appearance is caused by a combination of physical and biological factors such as the weakening of the arterial wall with increasing age [2], atherosclerotic changes, hypertension and smoking. This set of factors alters blood flow and, consequently, the vessel wall. Therefore, it is extremely important to obtain more information on how the different flow regimes affect blood vessels and brain aneurysms.

In vivo experiments are an effective way of investigating this pathology, but besides the ethical issues, these types of experiments are expensive and have low reproducibility

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[3]. *In silico* studies have been a widely used tool in recent years and have achieved substantial progress in the study of aneurysms. However, the limitation of numerical studies is the need for experimental validation, according to recommended international guidelines [4]. Thus, for a better understanding of the pathology and to study the blood flow inside aneurysms, it is necessary to develop *in vitro* models. These biomodels are suitable for refining endovascular treatments and validating theoretical and computational models [5].

In vitro models can be idealized or patient-specific [6]. Currently, the 3D printing technique has been used for the construction of the initial mold of the vessel lumen and polydimethylsiloxane (PDMS) is the material commonly used for the manufacture of biomodels. This material is transparent, biocompatible and can replicate the geometry of veins [7, 8]. Due to its advantages, PDMS has been used in a wide variety of applications in the biomedical field [9–17]. Pinho et al. [6] developed a biomodel of aneurysms in PDMS, based on clinical data, and this model was used for experimental studies using the digital image correlation technique and *in silico* tests [2, 18]. However, this model did not allow visualization of the flow within the cerebral aneurysm.

In order to improve the existing model, in this work, we propose a simple process to manufacture an *in vitro* PDMS cerebral aneurysm biomodel by combining rapid prototyping technology with a PDMS gravity casting process. Additionally, the model allows the visualization of the different behaviors of blood flow within the aneurysm. Thus, this work reports the acquisition of the real geometry of the cerebral aneurysm by using a prototyping technique to manufacture the mold and the biomodel in PDMS. It was also performed an experimental work of flow visualizations at different flow rates.

2 Materials and Methods

2.1 Geometry and Manufacturing Process

The geometry of the *in vitro* biomodel was obtained by performing image treatment from angiography images from a real cerebral aneurysm. The use of this type of geometry is essential to study the flow phenomena that occur within an aneurysm more realistically. Figure 1 illustrates the general measurements of the cerebral aneurysm model obtained from angiography images.

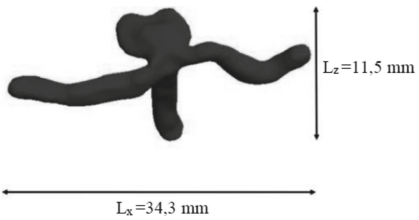

Fig. 1. General measurements of the cerebral aneurysm model.

The treated angiography images were converted into STL format and manufactured by means using a 3D printer model ProJet 1200 (3D Systems, USA). The geometry

was printed with the Visijet FTX Green resin as shown in Fig. 2. This process was chosen because the SLA (stereolithography) technique has good accuracy and high print resolution.

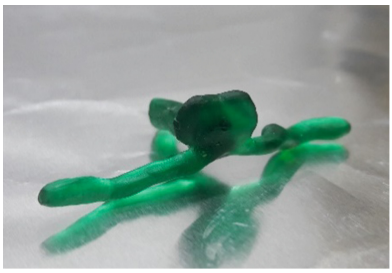

Fig. 2. Cerebral aneurysm model produced by the 3D Systems ProJet 1200 printer.

2.2 *In Vitro* PDMS Aneurysm Biomodel

To obtain the biomodel, the PDMS was prepared with a ratio of 10:1, i.e., 10 g of the PDMS base polymer correspond to 1 g of the curing agent. To perform the mixture, it was used a vacuum pump to remove the bubbles and after that, the physical model was placed in an acrylic box and the PDMS was poured into the mold by means of a gravity casting process. The curing period of PDMS was 48 h. In order to obtain the lumen of the blood vessel, the mold was placed in a glass beaker with acetone to remove the printed material. The described process is shown in Fig. 3.

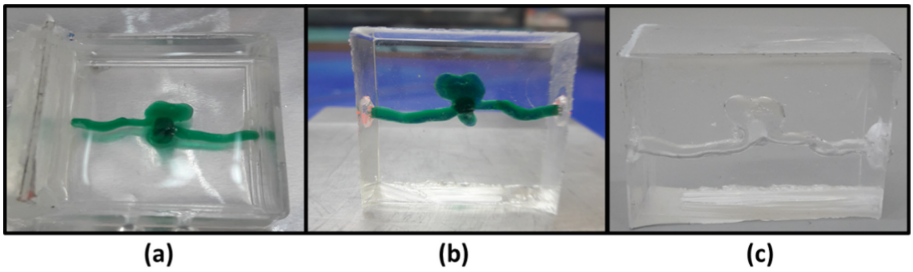

Fig. 3. Process of obtaining the transparent biomodel. (a) curing the PDMS in the acrylic box; (b) biomodel in PDMS with the printed model; (c) transparent PDMS biomodel with a cerebral aneurysm to perform the fluid experiments.

2.3 Flow Visualizations Setup

In the flow visualization tests, it was used a high-speed video microscopy system consisting of an inverted microscope (IX71, Olympus, Japan) combined with a high-speed

camera (Photron FASTCAM SA3) and an objective lens (ZEISS, 2.5 ×). To visualize the movements of the particles inside the cerebral aneurysm, it is necessary that the working fluid has the same value as the PDMS refractive index, which is 1.412. A particulate blood analog fluid composed of 61% glycerol and 39% water (w/w) was developed [19, 20] and this fluid has the same refractive index as PDMS, which allows the visualization of the particles. 0.1% of suspended Polymethylmethacrylate (PMMA) particles of 60 μm (diameter) were added to the fluid. The experiments were performed at room temperature (T = 20 ± 2 ºC). Figure 4 illustrates the experimental setup used to perform the flow visualizations. To process the images previously recorded was used the ImageJ software being the flow behavior automatically analyzed by the Z Project plugin [21].

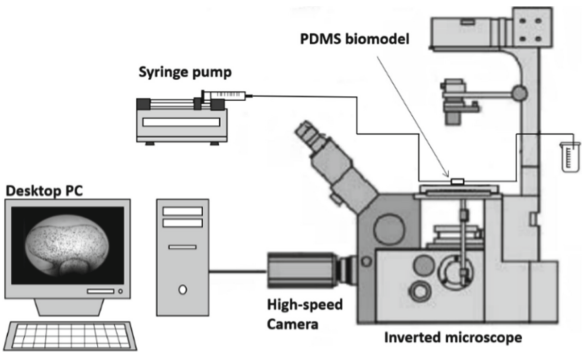

Fig. 4. Setup for *in vitro* experimental tests.

3 Results and Discussion

The developed cerebral aneurysm biomodels, in PDMS, proved to be suitable for experimental flow assays, managing to reproduce the geometry of the blood vessel and with good transparency.

To perform the flow visualizations, the PDMS biomodel was placed under the microscope and the analog fluid was injected into the biomodel through a syringe pump with a constant flow rate. In this study, it was tested different flow rates, i. e., 3 mL/min and 6 mL/min, in order to visualize the moment of transition of the flow behavior and the beginning of recirculation in the aneurysmal sac. The recorded images, shown in Figs. 5 and 6, were processed in the ImageJ software by using the Z Project plugin. With this plugin, the PMMA trajectories captured by a video record were converted automatically into one single image as is shown in Figs. 5 and 6.

From these flow experiments, it was shown that the manufactured PDMS biomodels were suitable to perform hemodynamic studies. Qualitatively, it is possible to observe (Figs. 5 and 6) that at the regions close to the channel inlet and outlet, typical laminar flows were observed for all the tested flow rates. However, when the trace particles get closer to the neck of the aneurysm, the flow tends to suffer a deviation into the direction of the aneurysm and as a result, it was observed the formation of vortices at a flow rate of 6 mL/min. In contrast, at a lower flow rate of 3 mL/min, no recirculation was observed.

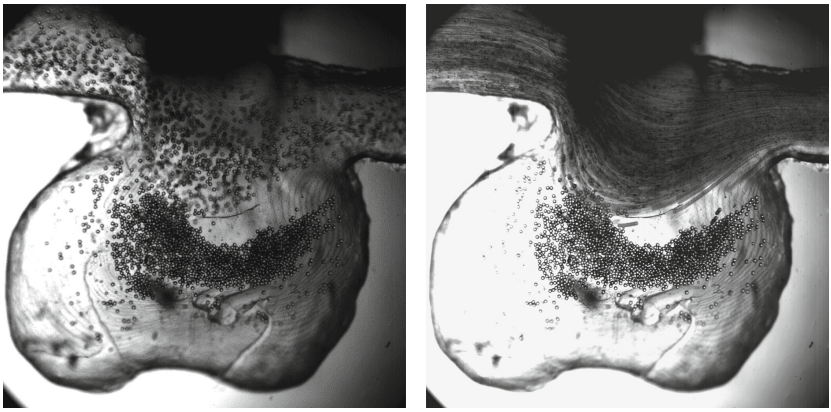

Fig. 5. Flow visualizations of the blood analogue fluid recorded from a high-speed camera at a flow rate of 3 mL/min of an individual recorded image (right side); treated by the Z Project plugin (left side).

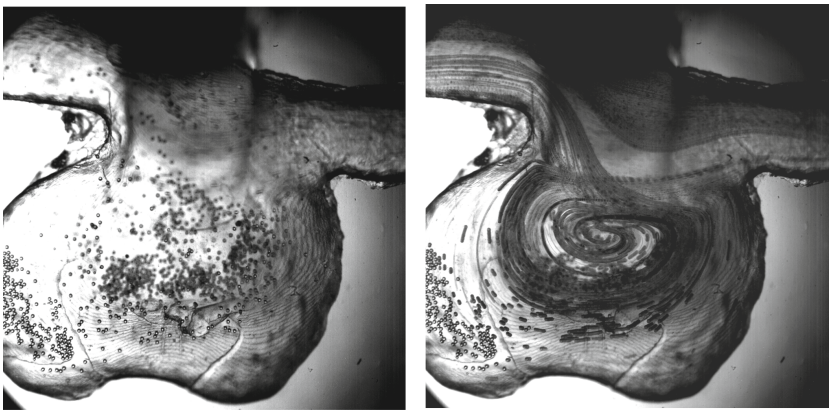

Fig. 6. Flow visualizations of the blood analog fluid recorded from a high-speed camera at a flow rate of 6 mL/min of an individual recorded image (right side); treated by the Z Project plugin (left side).

Hence, these qualitative results indicate that there is a transition from laminar to turbulent flow at a flow rate of about 6 ml/min. The experiments also demonstrate the potential for classifying blood flow patterns within the brain aneurysm. According to the study developed by Cebral et al. [22, 23] who showed that ruptured brain aneurysms are more likely to have complex flow patterns, unstable flow, concentrated inlet jets and small impact regions. Through the final images obtained, we can visualize a single recirculation region indicating a simple flow pattern. The change in flow behavior indicates flow instability. It is also possible to observe that only a part of the flow enters the aneurysmal sac, characterizing it as concentrated inlet jets. Although the flow rate used in the tests was lower than the actual flow rates of a cardiac cycle, the technique used in this study

indicates great potential and additional tests are in progress and will be published in due course.

4 Conclusion

It has been reported that the brain aneurysm is caused by a set of factors that are still not well understood. Although many numerical flow studies have been carried out still the majority of these models need to be validated. With the difficulty of performing *in vivo* assays, the *in vitro* study of aneurysms has proved to be an efficient alternative with great potential to validate numerical studies, test new medical devices and improve surgical techniques. However, in order to carry out an *in vitro* test, it is necessary to build biomodels that allow the visualization of the particulate flow. The proposed PDMS biomodels have the potential to be used as *in vitro* models and to study hemodynamics within a brain aneurysm, through the visualization of the flow. By using this flow visualization technique, it will be possible to identify the kinds of flow and to relate them to the flow patterns that the literature indicates as possible causes of aneurysm rupture. The used technique also shows great potential to assist in the development and validation of computational models.

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