DESIGN OF AN ACTUATION SYSTEM ABLE TO REPRODUCE THE BLOOD FLOW IN ARTERIES

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Abstract. *Heart diseases are often associated with abnormal flow in arteries. One of the most common is that known as atherosclerosis. In this, the deposition of fatty material in the blood vessels may cause their hardening and thickening, mostly in regions of low wall shear stress. Usually, a reduction of the vessel (stenosis) is the immediate effect. Subsequent developments (plaque rupture and platelet adhesion) can result in artery occlusion and may lead to serious cardiovascular failures such as thrombosis. Atherosclerosis is a slow, complex disease that typically starts in childhood and often progresses when people grow older. Atherosclerosis is the primary cause of morbidity and mortality in every industrialized nation. It is well-known that the important manifestation of a functioning cardiovascular system deals with its pulsatile blood flow in the arteries. The pulsatile blood flow has mainly three important characteristics, namely: flow velocity; pulse waveform; and velocity of pulse propagation. Heart rate is designated in beats per minute (bpm) with normal adult resting rates ranging from 60 to 100 bpm and a tremendous reserve capacity to more than triple these rates during challenge. Blood flow in arteries is unsteady due to the cyclic nature of the heart pump creates pulsatile conditions in all arteries. The blood is pumped out of the heart during systole. The heart rests during diastole, and no blood is ejected. The shape of the arterial pressure wave depends on several factors. The arterial pressure wave can be considered as being the summation of an incident and a reflected wave, and it is generally agreed that wave reflection and the physical properties of the arterial wall are significant factors responsible for propagating arterial pressure pulse changes. In order to develop a comprehensive understanding of the phenomena, various techniques have been deployed. One key aspect is the in vitro experimentation of blood flow under controlled conditions, using techniques not suitable to live specimens. Laboratory experiments enable the detailed characterization of the fluid flow in complex geometries, those most often linked with circulatory malfunctions. Thus, the development of suitably realistic experiments is of paramount relevance. This paper reports upon the design and development of a mechanism to replicate the blood flow in arteries. The system is able to duplicate the flow during the cardiac cycle by the use of specially designed form-closed cam-follower mechanism together with a hydraulic close-control device that actuates double effect rams. Further, the follower is rigidly attached to a hydraulic cylinder, which performs and controls the blood flow. In addition, a multi-port data acquisition together with appropriated computer software controls the reverse weeblood flow. The capability of the designed mechanism presented in this paper is a trade-off between natural idea of the blood flow and technical feasibility.*

Keywords: *Cardiac cycle, kinematic synthesis, mechanical design*

1. INTRODUCTION

Heart diseases are often associated with abnormal flow in arteries. Heart disease is one of the leading causes of death in the USA. One of the most common is that known as atherosclerosis (Antti, 2006, Chapman, 2006 and Jusztina, 2006). In this, the deposition of fatty material in the blood vessels may cause their hardening and thickening, mostly in regions of low wall shear stress (Gibson, 1993 and Farmakis, 2004). Usually, a reduction of the vessel (stenosis) is the immediate effect. Subsequent developments (plaque rupture and platelet adhesion) can result in artery occlusion and may lead to serious cardiovascular failures such as thrombosis (David and David, 1999 and Fragomeni *et al*, 2006).

Atherosclerosis is a slow, complex disease that typically starts in childhood and often progresses when people grow older. In some people, it progresses rapidly, even in their third decade. Causes of damage to the arterial wall include elevated levels of cholesterol and triglyceride in the blood, high blood pressure, tobacco smoke, diabetes, just to mention few. Atherosclerosis is the primary cause of morbidity and mortality in every industrialized nation (Reddy and Yusuf, 1998).

In order to develop a comprehensive understanding of the phenomena, various techniques have been deployed. One key aspect is the in vitro experimentation of blood flow under controlled conditions, using techniques not suitable to live specimens. Laboratory experiments enable the detailed characterization of the fluid flow in complex geometries, those most often linked with circulatory malfunctions.

Thus, the development of suitably realistic experiments is of paramount relevance. For such purpose, the effect of fluid viscosity and arterial wall properties will also be considered in the blood flow simulation. This paper reports upon the design and development of a mechanism to replicate the blood flow in arteries. The system is able to duplicate the flow during the cardiac cycle by the use of specially designed form-closed cam-follower mechanism together with an hydraulic close-control device that actuates double effect rams. Further, the follower is rigidly attached to an hydraulic cylinder, which performs and controls the blood flow. In addition, a multi-port data acquisition together with appropriated computer software controls the reverse blood flow. The capability of the designed mechanism presented in this paper is a trade-off between natural idea of the blood flow and technical feasibility.

The remainder of the paper is organized as follows. In section two the cardiac cycle is briefly reviewed and presented. The blood flow rate and the accumulated blood volume in the inferior aorta are also presented in this section. A short description of the overall mechanical system designed to replicate the blood flow in arteries is given in section three. Section four presents the process used to perform the synthesis of the cam-follower mechanism. In the process, the type of cam and follower types selected are discussed, as well as the methodology used to obtain the cam profile. Some results for the main kinematic parameters involved in the mechanism motion are presented and discussed in section five. Finally, in the section six the main conclusions from this study are presented and the perspectives for future research are outlined.

2. CARDIAC CYCLE

It is well-known that the important manifestation of a functioning cardiovascular system deals with its pulsatile blood flow in the arteries. The pulsatile blood flow has mainly three important characteristics, namely: flow velocity; pulse waveform; and velocity of pulse propagation. Heart rate is designated in beats per minute (bpm) with normal adult resting rates ranging from 60 to 100 bpm and a tremendous reserve capacity to more than triple these rates during challenge (Schneck and Bronzino, 2003).

Blood flow in arteries is unsteady due to the cyclic nature of the heart pump creates pulsatile conditions in all arteries. The blood is pumped out of the heart during systole. The heart rests during diastole, and no blood is ejected. The shape of the arterial pressure wave depends on several factors. The arterial pressure wave can be considered as being the summation of an incident and a reflected wave, and it is generally agreed that wave reflection and the physical properties of the arterial wall are significant factors responsible for propagating arterial pressure pulse changes.

The arterial pressure wave has an initial rapidly rising phase followed by an early systolic peak known as the percussion wave, followed by a second late systolic peak or bulge (the tidal wave). Following this second peak, there is a notch corresponding to aortic valve closure. During diastole, there is a gradual decrease of pressure as runoff proceeds to the peripheral circulation. There may be a third wave known as the diastolic or dicrotic wave (Schneck and Bronzino, 2003).

Velocity varies across the vessel due to viscous and inertial effects. Velocity profiles are complex because the flow is pulsatile and vessels are elastic, curved, and tapered. Backflow occurs during diastole, and profiles are flattened even during peak systolic flow.

The blood dynamics of a model of abdominal aorta was already simulated numerically by various authors (Lee and Chen, 2003, Wang and Parker, 2004 and Younis and Berger, 2004). Recently, (Taylor *et al*., 2004) has quantified the blood flow in supra-renal and infrarenal aorta, at resting and exercise conditions. Figure 1 shows the blood flow rate in the infrarenal aorta for a complete cardiac cycle, which is based on the work developed by Taylor *et al* (2004).

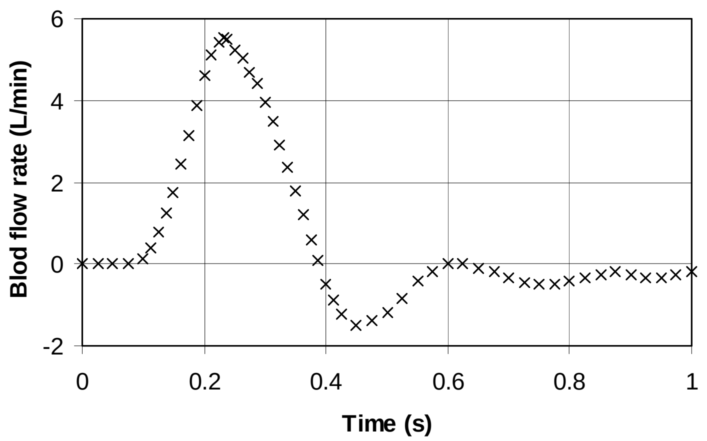

Figure 1. Blood flow rate in the infrarenal aorta {adapted from Taylor *et al* (2004)}.

Figure 2 presents the accumulated blood volume obtained from the integration, in time, of the blood flow rate depicted in Fig.1. From Fig.2, three different phases can be distinguished, namely:

(1) Heart blood pumped, which corresponds to the time interval from 0.1375s to 0.3875s. During this phase the blood is pumped by the heart to the arteries;

(2) Reverse or backflow blood, which corresponds to the time interval from 0.3875s to 0.8000s. This phase is characterized by the negative flow, that is, the blood flows in the reverse way in the arteries;

(3) Stationary phase, which starts at 0.8000s and finishes when the heart blood is pumped again (0.1375s). This phase closes the cardiac cycle.

These three phases are very important concerning with the definition of the follower displacement diagram, which is obtained from this information.

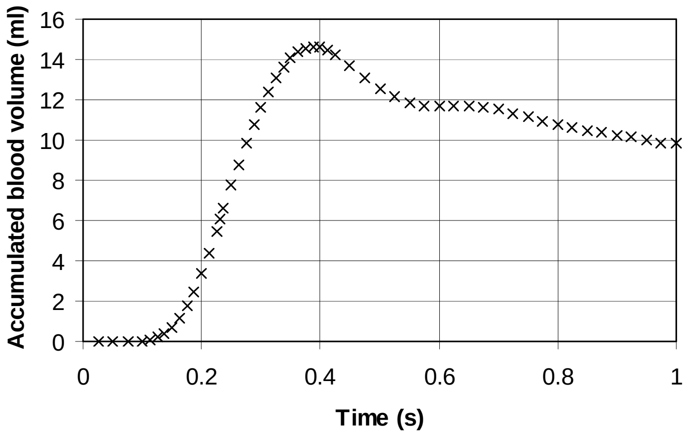

Figure 2. Accumulated blood volume in the infrarenal aorta.

3. MECHANICAL SYSTEM DESCRIPTION

The main purpose of the present work is to design and construct an experimental apparatus that will be able to reproduce the blood flow in arteries. Figure 3 depicts an overall representation of the developed system.

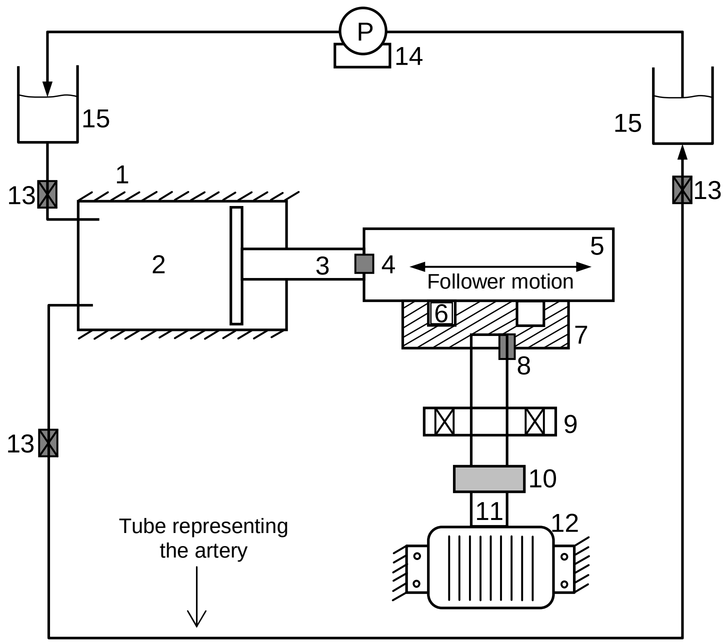

Figure 3. Schematic representation of the mechanical system.

Figure 3 shows, schematically, a representation of the overall mechanical system, which includes the following components: ground (1), hydraulic cylinder (2), cylinder rod (3), rigid joint (4), linear bearing (5), roller follower (6), form-closed cam (7), cam-shaft connection (8), journal-bearing (9), flexible union (10), shaft (11), motor (12), valve (13), pump (14) and tank (15).

4. CAM-FOLLOWER MECHANISM SYNTHESIS

The accumulated blood volume in the infrarenal aorta, that represents the cardiac cycle, is supplied by an hydraulic cylinder as illustrated in Fig. 3. The volume of this cylinder is known. In turn, the cylinder is actuated by the use of specially designed form-closed cam-follower mechanism. This type of cam-follower mechanism was selected due to its capability and versatility to ensure the complex motion profile due to the cardiac cycle. Thus, from the accumulated blood volume in the infrarenal aorta represented in Fig.2, the follower displacement was calculated using the relation

$$s = f(V,\phi) \tag{1}$$

where s is follower displacement, V represents the accumulated blood volume and ϕ is the cylinder diameter.

In the present study, the period of the cardiac cycle is considered to be equal to 1 second, which corresponds to 60 bpm. Thus, the follower displacement diagram, which includes the three different blood flow phases, can be represented as it is illustrated in Fig. 4.

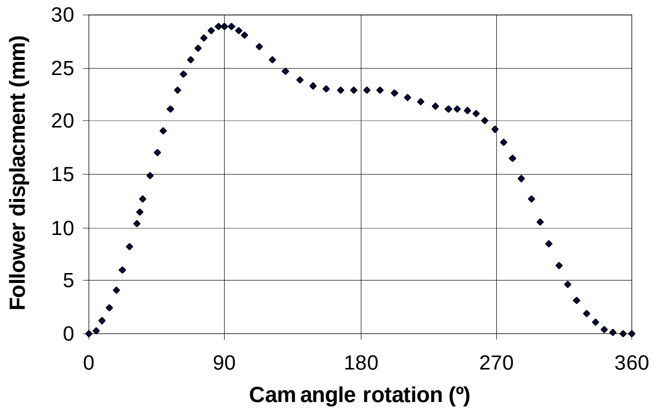

Figure 4. Follower diagram obtained from the accumulated blood volume.

The sequence of the follower motion is described by a rise, followed by two falls. The rise is relative to the cylinder rod return forced by the follower, and the two falls are associated with the advance of the cylinder rod. In the beginning of the return phase the cylinder is full of blood and this blood if totally supplied to the artery. On the other hand, the advance phase of the cylinder is filled with blood from artery (first fall) and from the tank (second fall). In the second fall new blood is supplied to the system.

The rise, which corresponds to the heart blood pumped to the system, is represented by the interval of cam angle rotation from 0 to 90º, and the maximum follower displacement is equal to 28.52mm. The first fall represents the reverse blood flow, which starts at 90º with 148.5º of amplitude. The second fall corresponds to the aspiration of new blood from the tank. This phase has amplitude equal to 121.5º that corresponds to the end of the complete cam rotation.

The mathematical equations for the first two follower motion phases were obtained by the use of polynomial functions that approximate the discrete data to continuous functions. This purpose was reached through the use of advanced mathematical tools, namely the software MuPAD (acronym for Multi Processing Algebra Data Tool). This process has been facilitated by this computational facility, which provides some important advantages when compared to graphical design, such as more precision and accuracy. The last follower motion, which corresponds to the second fall, is of cicloidal type.

The cam profile was obtained based on the theory of envelopes. In a similar way to the traditional approach, the desired positions of the follower are determined for an inversion of the cam-follower system in which the cam is held stationary. The cam that will produce the desired motion is then obtained by fitting a tangent curve to the follower positions. Unlike, the graphical approach, however the analytical approach can consider a virtually unlimited number of continuous follower positions as opposed to a finite number of discrete positions in a graphical layout (Norton, 2002, Chen, 1982 and Shigley and Uicker, 1981).

In what follows, the main characteristics of the cam profile are presented. In the present work a radial cam and a translational follower roller are used. The family of circle curves describes the roller follower is given by,

$$F(x,y,\theta)=(x-x_C)^2+(y-y_C)^2-R_f^2 \tag{2}$$

where Rf is the roller radius and (x_C,y_C) are the coordinates of the center roller, which can be determined as follows,

$$x_C=-(R_b+R_f)\cdot sen\theta - s\cdot sen\theta \tag{3}$$

$$y_C=(R_b+R_f)\cdot cos\theta + s\cdot cos\theta \tag{4}$$

where R_b is the cam radius base, and θ is the parameter of the family circles.
Differentiating Eq. (2) yields,

$$\frac{\partial F}{\partial\theta}=-2(x-x_C)\frac{dx_C}{d\theta}-2(y-y_C)\frac{dy_C}{d\theta}=0 \tag{5}$$

and from Eqs. (3) and (4) results,

$$\frac{dx_C}{d\theta}=-(R_b+R_f)cos\theta - s\cdot cos\theta-\frac{ds}{d\theta}sen\theta \tag{6}$$

$$\frac{dy_C}{d\theta}=-(R_b+R_f)sen\theta - s\cdot sen\theta+\frac{ds}{d\theta}cos\theta \tag{7}$$

where $ds/d\theta$ represents the follower velocity.
Solving Eqs. (2) and (5) simultaneously gives the coordinates of the cam profile,

$$x=x_C\pm R_f\left(\frac{dy_C}{d\theta}\right)\left[\left(\frac{dx_C}{d\theta}\right)^2+\left(\frac{dy_C}{d\theta}\right)^2\right]^{-\frac{1}{2}} \tag{8}$$

$$y=y_C\mp R_f\left(\frac{dx_C}{d\theta}\right)\left[\left(\frac{dx_C}{d\theta}\right)^2+\left(\frac{dy_C}{d\theta}\right)^2\right]^{-\frac{1}{2}} \tag{9}$$

Note the plus and minus signs in Eqs. (8) and (9) reflect the fact that they are two envelopes, an inner profile and an outer profile, as it is illustrated in Figure 5, which represents the cam profile obtained in the present work.

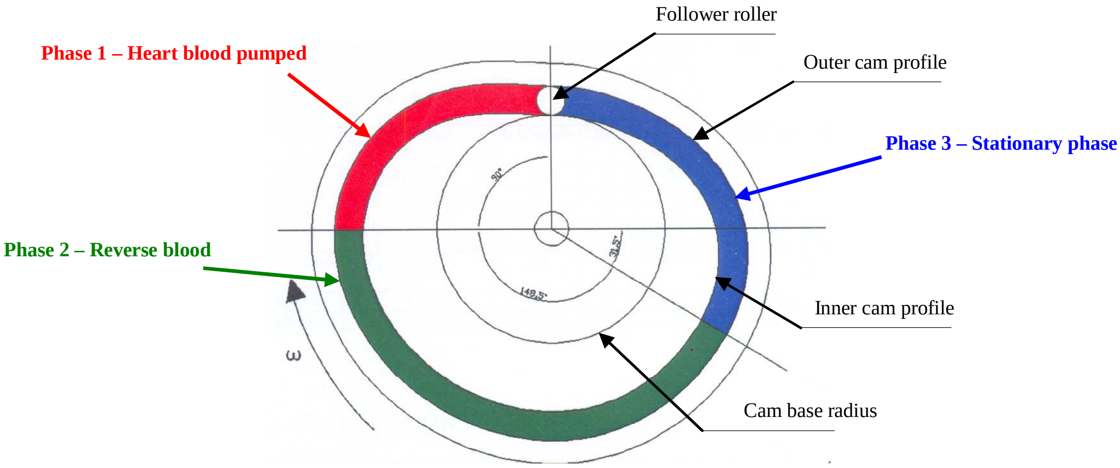

Figure 5. Closed-form cam profile obtained with the three main phases.

5. KINEMATIC ANALYSIS

In the section, the main kinematic parameters associated with the follower motion are analyzed. The follower displacement was already presented and discussed in the section before. Since the mathematical equations for the different follower phases are know, the other kinematic characteristics (velocity, acceleration and jerk/impluse) of the follower motion are obtained by successive differentiations of the respective displacement equations.

Figures 6, 7 and 8 depict the follower velocity, follower acceleration and follower jerk. It should be noted that with the objectives of the present work, there is continuity in the follower velocity and acceleration diagram, which was ensured in the numerical process. Furthermore, the jerk curve, besides presents three discontinues, their values are finites and, consequently, ensure a soft motion between the cam and follower.

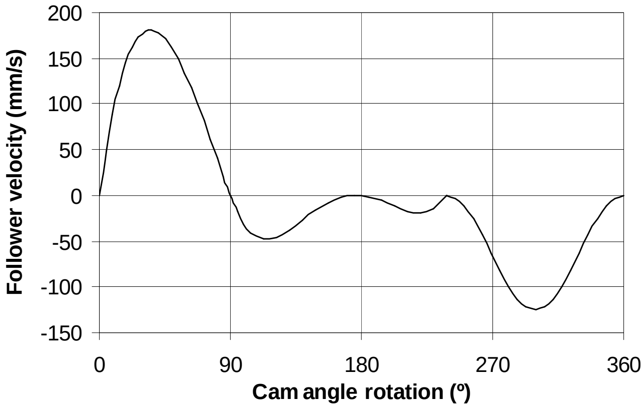

Figure 6. Follower velocity for a complete cam rotation.

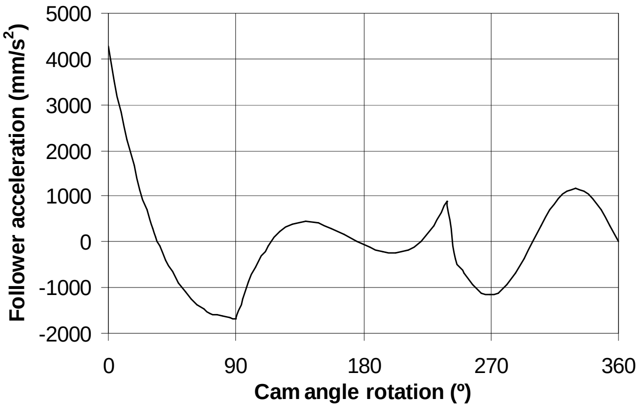

Figure 7. Follower acceleration for a complete cam rotation.

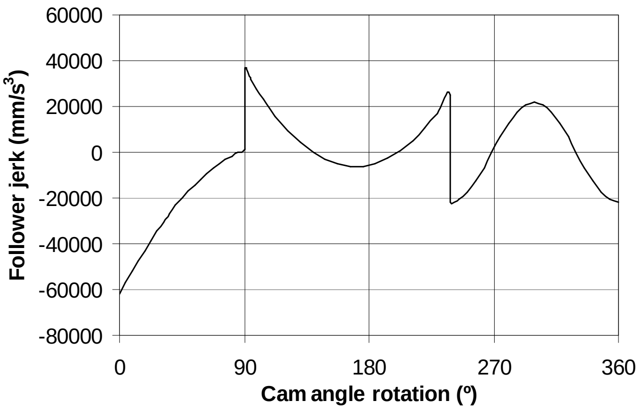

Figure 8. Follower jerk for a complete cam rotation.

With the main purpose of validating the profile obtained for the cam a numeric analysis was performed using an advanced mathematical tool, namely the software Working Model.

For that, initially the closed-form cam was drawn starting from the theoretical profile obtained previously, as well as the follower and the guide, being made afterwards the export for the numeric simulation software Working Model, as shown in the Figure 9.

Figure 9. Working Model simulation of the closed-form cam.

Figure 10 presents the follower displacement results of a numeric simulation. It can be concluded that the profile of the closed-form cam it was well done, because the numerical follower displacement results are very close of the values required to simulate adequately the period of the cardiac cycle, that were previously presented in the figure 4.

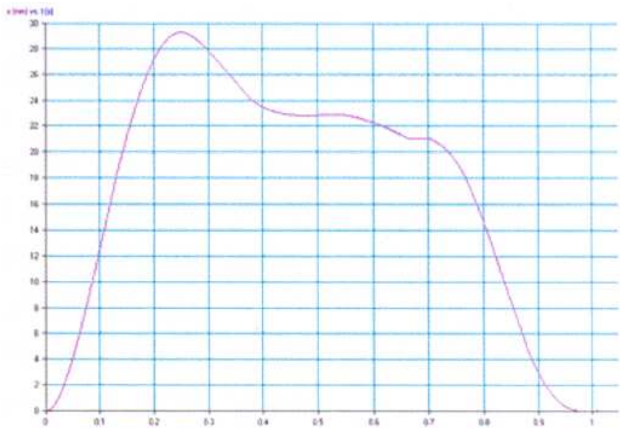

Figure 10.Numerical follower displacement of the closed-form cam.

6. CONCLUSIONS AND FUTURE WORK

The kinematic synthesis of a cam-follower mechanism able to replicate the transient blood flow in arteries has been presented and discussed throughout this work. Based on experimental data, relative to the infrarenal aorta blood flow, were used to obtain the follower displacement. Then, the cam profile was determined by the use of the theory of envelopes. In the process, the kinematic analysis of the follower motion was performed.

This work reports on an initial phase that corresponds to the design and construction of an experimental apparatus, which will be allow to test and validate numerical simulations of the blood flow in arteries.

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