HYDRODYNAMIC SIMULATOR FOR STUDIES "IN VITRO" OF THE CARDIOVASCULAR SYSTEM

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Abstract. The present work refers both to the improvement and optimization of a cardiovascular simulator for the evaluation of the resistance of blood vessels. This work follows a Master and a PHD work in medicine research developed at Escola Paulista de Medicina/UNIFESP, according with *a "Protocolo de Intenções"* signed by Universidade de São Paulo/Escola Politécnica – EPUSP, Universidade Federal de São Paulo/Escola Paulista de Medicina – UNIFESP/EPM and Instituto Dante Pazzanese de Cardiologia – IDPC, in April/1996, which had a duration of five years. The simulator consists basically of two parts: a central unit of pulsing flux and pressure to generate a wave pulse and a modular unit in which the various blood vessel tests were done.

The vein segments used were obtained from surgery procedure of Saphena overpass and varix surgery. These segments were carefully removed during surgeries and after the choice of surgeons, the reminiscent and totally discarded parts of vascular segment presenting a good shape were used in the simulator, instead to go to incinerator.

The calibration system was performed before vein rupture test. With the aid of an electromagnetic flow meter and Bourdon manometers, it was possible to get results of volumetric flux and pressure in the test section.

The pressure values reached for vein segment ruptures are on the order of 300 kPa or more, showing the high resistance of the vein wall structure.

Keywords. Cardiovascular Simulator, Vascular Rupture, Vascular Flow

1. Introduction

The human body can be see as an integrated system of fluid, where large flow scales (circulatory system, by instance) and small flow scales (microcirculation , individual cells movement) are presented.

Law et al (1987) reported that blood flow through arteries and veins have been studied extensively in terms of pulsatile flux propagation under pressure pulses, which is important as an auxiliary help in the diagnosis of vascular diseases.

Walker (1995) comment that the larger artery of our body is the aorta with an area of almost 2,5 cm^2, which means an area 2500 times greater that some capillaries. The aorta has a ticker wall because it receives the blood that is pumped from the left ventricle and need to resist to the higher pressure of the body system. The larger veins of our body is the cava, which is responsible for the blood transportation to the high side of the heart. This vein has diameter of 2,0 cm, approximately, but the walls are less ticker that aorta walls.

The blood flow behavior in arterial and vascular systems have been studied through mathematical (or computational) and physical experimental models (*in vitro* modeling research) (see Mazza & Rosa 1995 and 1998) and the work here presented integrate this last category of model representation. The hydrodynamic simulation (*in vitro* study) of blood vessels is an old and important tool for research of the factors which affect the hemodynamic (aneurysms, sutures, prostheses, bifurcations, vessel elasticity etc).

Guerino (1998a and 1998b) reported a simulator idealization consisted basically of two parts: a central unit of pulsing flux and pressure to generate a wave pulse and a modular unit in which the various blood vessel tests were done.

With the objective to develop joint activities in biomedical engineering, in April of 1996, it was signed by *Universidade de São Paulo/Escola Politécnica – EPUSP, Universidade Federal de São Paulo/Escola Paulista de Medicina – UNIFESP/EPM and Instituto Dante Pazzanese de Cardiologia – IDPC* a *Protocolo de Intenções*, with a duration of five years. During this period, some master and PHD works were developed in both *Escola Paulista de Medicina e Escola Politécnica*, which involved *in vitro* simulation. A result of some of these works was the improvement, calibration and tests of the cardiovascular simulator system here presented.

2. Objective

The main objective of this work is the improvement and the optimization of a hydrodynamic simulator for the study of blood vessels resistance, so that could be possible a better understanding of the hemodynamic conditions an of some characteristics of the vascular segment.

The experimental investigation is based in a pulsatile flux generator which reproduce the physiologic wave form in the main artery tree and, considering the simulation in a vessel (vein segment) where we want to know the pressure resistance to rupture.

3. Experimental Installation

3.1. Description of the Experimental Installation Used

The experimental installation used for tests can be viewed through Fig (1).

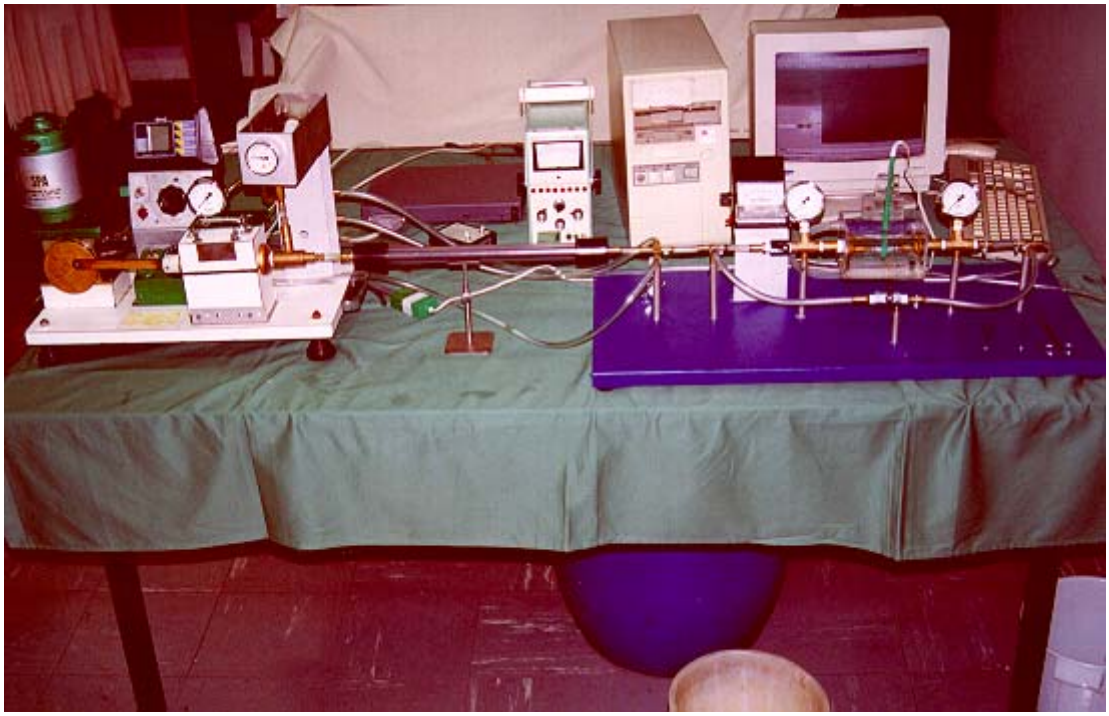


Figure 1. Experimental Installation Used .

The experimental installation consists of: a raised reservoir with a thermostat accomplished together; a pumping system, consisting of a piston guided by a came, which is moved by a continuous current motor and a redutor system and is controlled by a frequency pulse current; alimentation pipe; two unidirectional valves which simulate the behavior of mitral and aortic valves; a simulator system for the ventricle system; a module to reproduce the complacence; a test model region, where it is possible to measure the flux using an electromagnetic flow meter, and which output data results can be followed in a real time through a data acquisition system accomplished to a microcomputer. Others equipments like: manometers, valves, flux regulators, drainage system, *tourniquet* and a microamperimeter, complete the experimental set simulator.

Figure (2) presents an schematic view of the experimental set used.

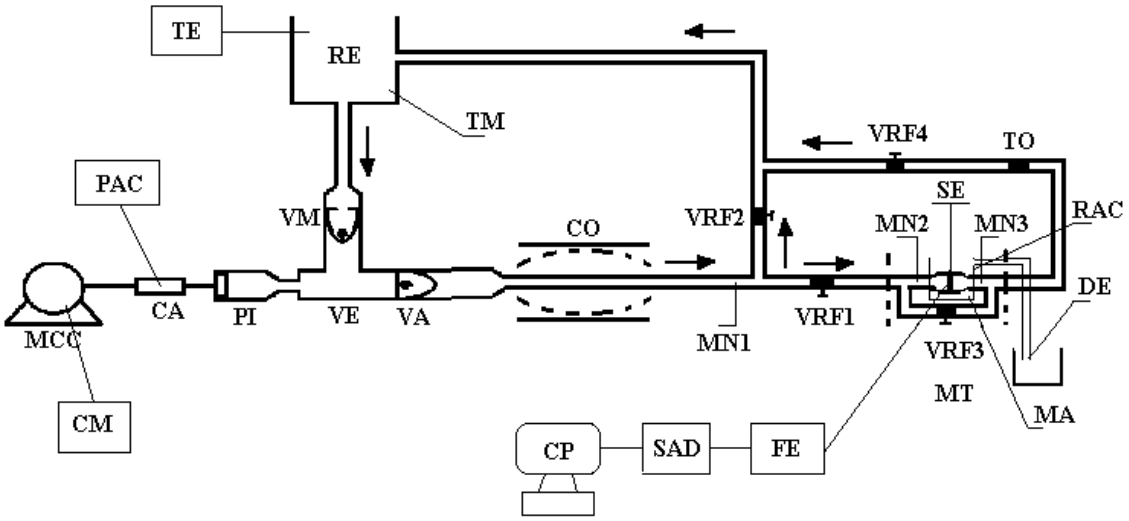


Figure 2. Schematic representation of the experimental installation, where: **RE –** Reservoir; **TE** Thermostat; **TM** Thermometer; **PAC** Control panel; **MCC** Motor of continuous current; **CM** Controlling motor system; **CA** Came; **PI** Piston; **VM** Mitral valve; **VE** Left ventricle; **VA** Aortic valve; **CO** Complacence module; **MN1** Manometer; **MN2** Manometer; **MN3** Manometer; **DE** Drain; **RAC** Acrylic reservoir; **TO** Tourniquet, **VRF1** Flux regulator valve, responsible for the flow alimentation of the test section; **VRF2** Flux regulator valve, responsible for the rapid return flow to the reservoir; **VRF3** Flux regulator valve, responsible for the collateral circulation; **VRF4** Flux regulator valve, responsible for the rapid return flow to the reservoir; **MT** Test module; **MA** Microamperimeter, **SE** Electromagnetic sensor; **FE** Electromagnetic flow meter; **SAD** Data acquisition system; **CP** Computer; and → is the indication of the flow direction.

3.2. Work Mechanism Principles which Support the Simulator System Used

The work mechanism principle of the simulator system is based in the ventricle function. The piston works increasing the pressure in the interior of the ventricle, the mitral valve is closed and when the left ventricle pressure is greater that the system pressure, the aortic valve is opened and the fluid flow from the ventricle to the system (systole). When the piston returns to the initial position, the pressure in the ventricle is diminished until a value which is smaller that of the system pressure, so that, the aortic valve is closed and the mitral valve is opened, permitting that the fluid from the reservoir flows to the ventricle (diastole).

The complacence module works in the following manner. During the systole its wall is expanded which is responsible to maintain the pressure during the ventricular diastole (simulation of the arterial complacence). This module also has the function to avoid that the pressure gradient closes the vessel segment during the test.

The flux regulator valves have the objective of control the flow discharge through the test section.

The *tourniquet* has the objective of increase the peripherical resistance of the system so that could be possible to increase the pressure at the test section and to get conditions for the segment vascular rupture.

The drain has the objective to indicate the occurrence of leakage or vascular rupture in the test section.

3.3. Description of the Calibration System Used

The calibration system used in this work consists of a constant level reservoir, which supply the test section module, where the flux is controlled by an electromagnetic sensor connected to a flow meter and to a data acquisition and computer system. Manometers, valves for flux regulation, drain system and a Becker also are integrant parts of the calibration system. The basic idea was to get a steady flow in the vessel segment test section, measuring the volumetric flux downstream by using a Becker and a chronometer, and comparing these results with the electromagnetic flow meter and the data acquisition system results.

4.Experimental Procedure

4.1. Vein Preparation for the Rupture Test

For test simulation it was used saphena magna from human (vein segments totally discarded for incineration of saphena bridge surgeries and *safenéctomias*). These vein segments were tested previously (see Figure 3), so that it could be possible to guarantee that the vein segment received for the test were in good shape without any local dilatations or leakage through some possible incisions.

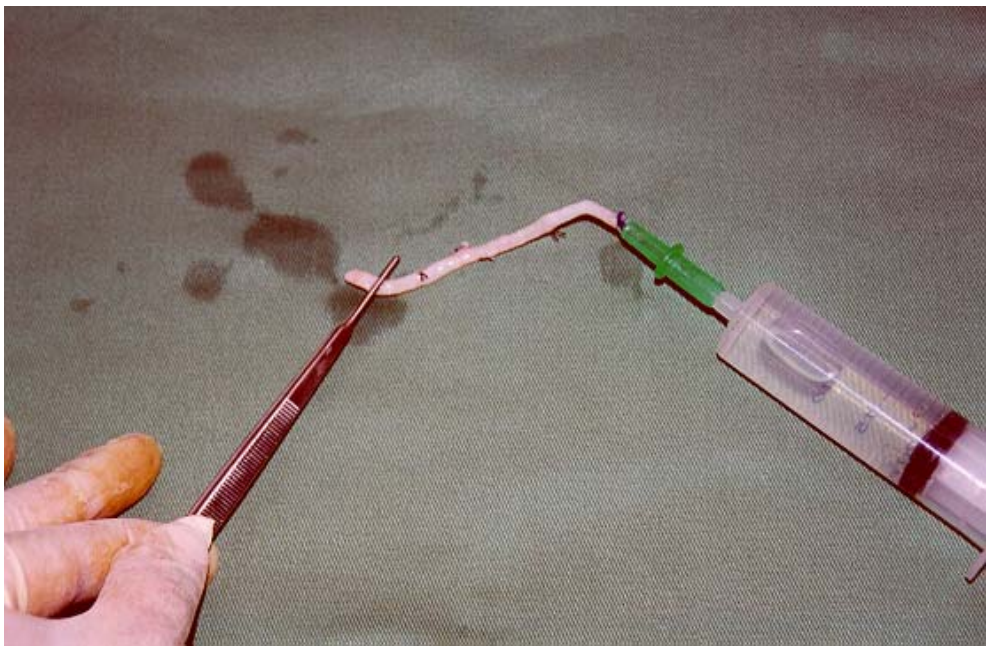


Figure 3. Visualization of the previous test of a vein segment received from surgical procedure.

Belzer & Southard (1988) reported that during the inspection of the vein segment, special care was taken to avoid traction or harsh movement that could damage the vein.

The vein segments were sectioned with 50 mm of length, observing he number of collaterals and limiting in two the number of sutures. Another factor which was take in consideration for the vein segment choose was its external diameter which should be not smaller that 3,5 mm.

4.2. Vein Segment Preparation at the Test Section

After the vein segment selection, by a medical doctor, the same was mounted in the test section, according with its diameter. Several *"canulas"* were constructed to fix the vein to the test section which could have an external diameter varying from 2,5 to 6 mm, with increments of 0,5 mm. After the introduction of the vein segment in the *"canula"* it was fixed with suture line No.4-0 of blue polypropylene.

4.3. Procedure to Choose the Work Fluid

Guerino (1998b) comments that the work fluid was chosen having as a main function to simulate the blood flow conditions at the region of the vein tested. Obviously the blood cannot be used as the work fluid, considering the difficulties to obtain that, the operation *in vitro* and the high level of hemolysis caused by the simulator. So, the option was the use of a physiologic water solution composed of NaCl 0,9%, which is an isotonic solution capable to maintain the vascular structure during the tests.

4.4. Methodology of Tests

First of all, the reservoir and the acrylic box at the test section were filled with the work fluid and the thermostat was turned on, so that the liquid temperature could reach 37°C, which corresponds to the mean body temperature.

After the regulation of the temperature, the motor was turned on, and the frequency was regulated in 60 r.p.m.

The first phase of the test was done with the flux regulator valves **(VRF)** totally opened, so that the pressure in the fluid flowing could be smaller as possible and the bubbles could be eliminated. This part of test had the duration of nearly 5 minutes, and it was registered the fluid pressure in the vein segment and the volumetric flux through that.

After to finish the first phase of test, the flux regulator valves of fast return **(VRF2)** and of collateral circulation **(VRF3)** were closed. At this moment, the volumetric discharge through the test section was increased, increasing also the pressure in the flow. The duration of this second phase was also 5 minutes, and the frequency was maintained at 60 rpm.

In the last phase of test it was tried the rupture of the vein segment, increasing the peripheral resistance downstream the test section with the help of a *tourniquet* and a flux regulator valve **(VRF4)**, which are responsible for the flux return to the test section. This phase of test was limited to 300 kPa, as a maximum pressure, to avoid the collapse of the complacence module and of valves system for higher values of pressure.

5. Results

5.1. Identification of the Magna Veins

It is presented in the table below a resume of the identification of the discarded vein segments used in this work:

Table 1. Identification of magna veins.
P.S = Saphena Bridge.
SA = Safenéctomia.

Tests	Sex	Age years	Mass Kg	Diameter mm	No. of collaterals Vein segment of 50 mm	N° of collaterals Vein segment used in the test 30 mm	Surgical technique
1	Mas.	59	81,9	5,5	2	0	P.S
2	Mas.	59	81,9	5,5	2	1	P.S
3	Mas.	59	81,9	5,0	0	0	P.S
4	Mas.	57	66,5	4,0	0	0	P.S
5	Mas.	57	66,5	3,5	0	0	P.S
6	Mas.	65	82	5,0	1	1	P.S
7	Mas.	52	79	3,5	1	1	P.S
8	___	___	___	4,5	2	1	P.S
9	___	___	___	4,0	0	0	P.S
10	Fem.	41	70,5	6,0	0	0	SA

5.2.Calibration Results

Many tests were done during the calibration phase, with comparison of the results obtained though the measurement of the real flow (Becker and chronometer) and obtained through data acquisition system.

The table below shows some results of the volumetric flux measured in this phase.

Table 2. Comparative results in between the values presented by data acquisition system and the value measured using Becker and chronometer.

Tests	Data Acquisition System Q(ml/min)	Real flux Q(ml/min)
1	180	205
2	310	360
3	470	580
4	450	540
5	460	550

It is interesting to emphasize that the real volumetric flux measured was always greater that the values observed in the data acquisition system in the range of 15 to 20% of difference. After several tests of calibration it was possible to conclude that the way how the flow meter was positioned embracing the vein segment had an influence in the values get in the computer, and that conclusion help in the improvement of the measurement conditions.

5.3. Results of First Phase of Tests

As was mentioned early that the first phase of tests was done with flux regulator valves **(VRF)** totally opened. The measured pressure values are presented in the table below:

Table 3. Pressure measurement during the first phase of tests.

Test	Diastolic Pressure (kPa)	Systolic Pressure (kPa)
1	0	10
2	0	10
3	0	10
4	0	10
5	0	10
6	0	10
7	0	10
8	0	10
9	0	10
10	0	10

5.4. Results of Second Phase of Tests

According with was previously described, the second phase of tests was done with the valves **VRF2** e **VRF3** completely closed. Table 4 shows the pressure measurements results in this test condition.

Table 4. Pressure measurement results for the second phase of test.
A = Small and not continuous leakage was observed.
B = Small and not continuous leakage was observed.

Test	Diastolic Pressure (kPa)	Systolic Pressure (kPa)	Observed Occurence
1	10	30	A
2	10	40	___
3	0	50	B
4	50	100	___
5	40	90	___
6	20	60	___
7	50	200	___
8	40	70	___
9	40	70	___
10	10	30	___

5.5. Results of Third Part of Tests

According with was previously described, in the third phase of tests it was tried the rupture of the vein segment by increasing the pressure in the test section, which was possible by increasing the downstream resistence with the help of a *tourniquet* and closing **VRF4**. The table below shows the pressure measurements results in this test condition.

Table 5. Pressure measurement results for the third phase.
A and B = Small and not continuous leakage was observed.
C = Total rupture occurred.

Tests	Maximum Pressure (kPa)	Occurences
1	300	A
2	300	No Rupture
3	300	B
4	300	No Rupture
5	300	No Rupture
6	300	No Rupture
7	300	No Rupture
8	300	No Rupture
9	300	No Rupture
10	220	C

The volumetric flux variation in time for the third phase is presented in the following figure:

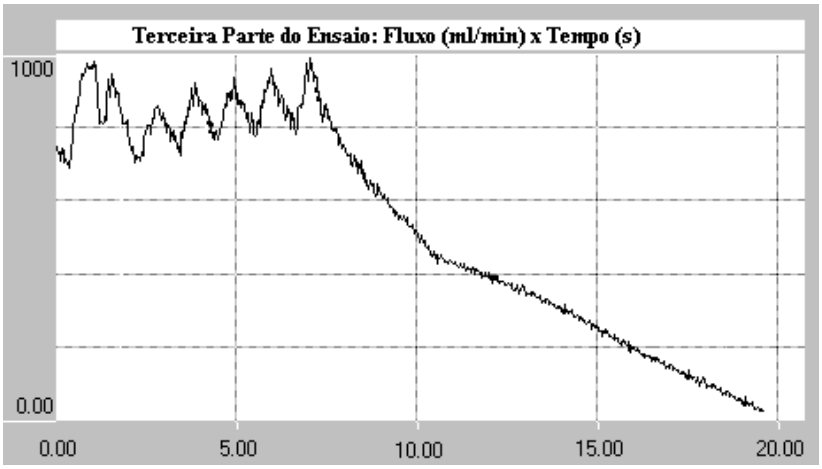


Figure 4. Volumetric flux variation as a function of time

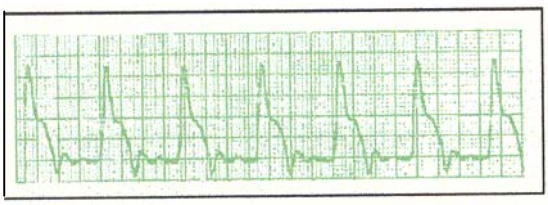
5.6. Unexpected Results During the Calibration Tests

It is important to emphasize that during the calibration tests it was mounted, accidentally, in the test section, a vein segment, with an internal valve in position to open against the flux. The result was that do not have flux and the vein resist to a pressure of 7 kPa. The course inversion of the mounted vein instantaneously permitted the flow through the vein. So, we learned, through the experimentation, that the valves of the venous system works one directionally.

5.7. Comparison Between a Femoral Physiological and the Simulator Signal.

Leal (2001) compares the outflow signal measured in the test section of the hydrodynamic simulator with the signal measured in conditions physiological.

Physiological Femoral Signal



Test Section Simulator

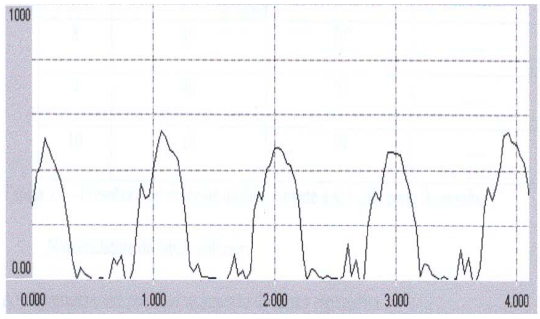


Figure 5. Comparison between test section simulator and physiological femoral signal.

The signals presented above are similar, which means that the reproduction of physiological conditions in the simulator are satisfactory.

6. Conclusion

The hydrodynamic simulator used in this work is useful to test vessel segment considering the end pressure scale of 300 kPa, which is much greater that the physiological levels (in the range of 10 to 20 kPa). In the great majority of the cases tested it was not possible to get the vein rupture.

The results showed that, although the collateral sutures of the vessels done by the medical doctors, these vessels support the high pressure (until the end of scale of the equipment 300 kPa).

From the analysis of the results presented in this work, it is possible to conclude that the vessel is ***design*** to support pressures much higher that the physiological levels of pressure. This information could help in the development of new techniques of surgical medical procedures applied to the circulatory system. This research also open the possibility to study vascular substitutes for cardio-vascular surgeries (like saphena bridge), without the necessity to remove the saphena vein from the patient.

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8.Acknowledgment

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