Characterization of Blood-Analog Fluids in a 180-degree Curved Artery Model

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Biofluid Dynamics Laboratory

Motivation

- Blood is a complex fluid comprised of red blood cells, leukocytes, plasma, and numerous other components.
- The arterial network consists of branches and curvatures that are present throughout the human vasculature. Within them, vortical patterns occur due to imbalances between pressure and centrifugal forces. (Figure 1)

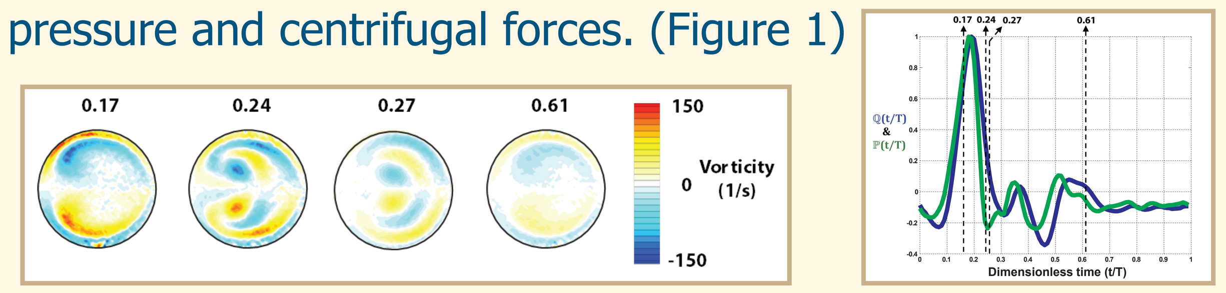


Figure 1: Vortical Pattern Progression Through Carotid Artery Waveform

- The presence of these patterns are believed to play a protective role in preventing aortic arterial wall damage, while the lack of them is linked to various diseases such as renal artery stenosis. [4]
- Realistic modeling has the potential to explain the role of complex blood flow structures in cardiovascular diseases like atherosclerosis, a leading cause of death in the developed world associated with plaque build up in the near-wall regions of curved arteries. (Figure 2)

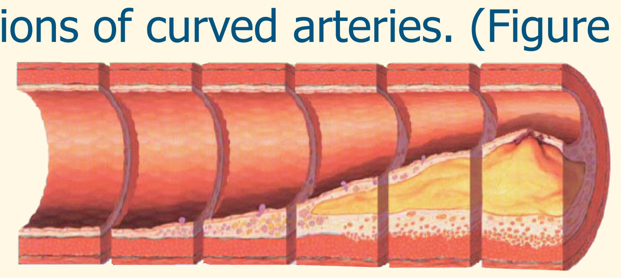


Figure 2: Atherosclerosis Progression
https://upload.wikimedia.org/wikipedia/en/6/66/Atherosclerosis_disease_progression.png

- A validated experimental model will lead to early detection of diseases and more specific patient care.

Background

- Using human blood is not feasible due to its short shelf life and storage problems, red blood cell coagulation, and lack of optical acess for acquiring optical measurements.
- In order to properly study cardiovascular fluid dynamics, blood-analog fluids must be created having the ability to mimic the material properties of blood and realistically respond to physiological flow stimuli.
  - These requirements allow for the potential of the experimental model to provide patient-specific care through unique flow stimuli and stenosis.
- Physiological flows in the core regions of large-diameter, curved blood vessels, e.g. the carotid artery, are assumed to exhibit Newtonian-like flow behavior.
  - In a Newtonian fluid, shearing stress is linearly related to the rate of shearing strain (Figure 3), e.g. as for water. [1-3]

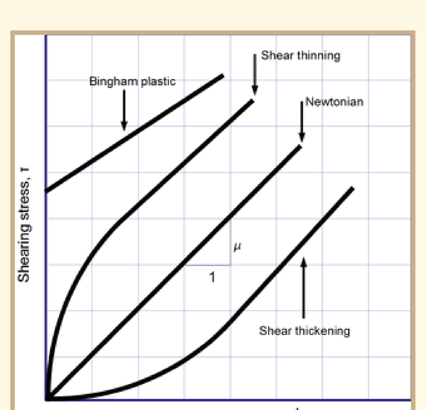


Figure 3: Stress vs. Strain Graph for Various Fluids
http://en.wikipedia.org/wiki/Viscosity

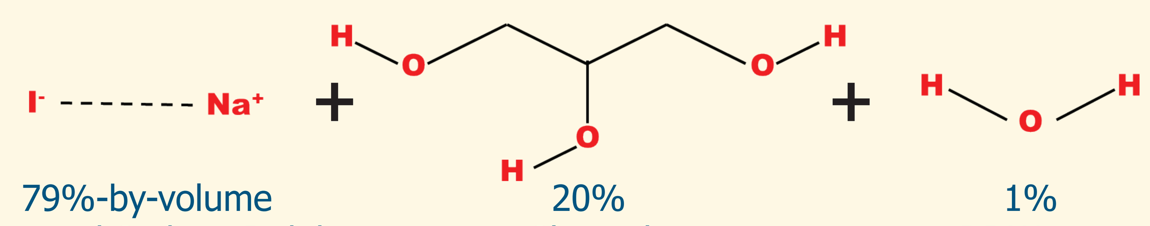
Objective

This study aims to determine the physiological effects of blood rheology by developing realistic blood-analog fluids which aid in characterizing the hydrodynamics of blood flow in large-scale curved blood vessels. The objective of this project is to create a simple blood-analog fluid using potassium thiocyanate (KSCN).

Experimental Setup & Method

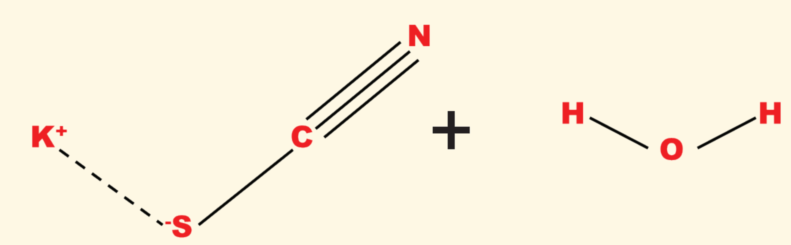
Chemical Compositions of Newtonian Fluids:

Fluid 1: NaI-based



79%-by-volume Saturated Sodium Iodide + 20% Glycerol + 1% DI Water

Fluid 2: KSCN-based



68%-by-weight Potassium Thiocyanate + 32% DI Water

- Three experiments were used to characterize the blood-analog fluids:
  1. Hydrodynamic Measurements
     - Estimate pressure and flow rate under carotid-artery based physiological flow conditions.
     - Pressure catheters, Flow rate sensor
  2. Rheological Measurements (Figure 4)
     - Estimate density, dynamic and kinematic viscosity.
     - Ubbelohde viscometer, Rheometer
  3. Optical Measurements
     - Refractive index measurements to aid non-invasive, laser based flow field measurements.
     - Handheld Refractometer

Figure 4: Ubbelohde Viscometer, Rheometer

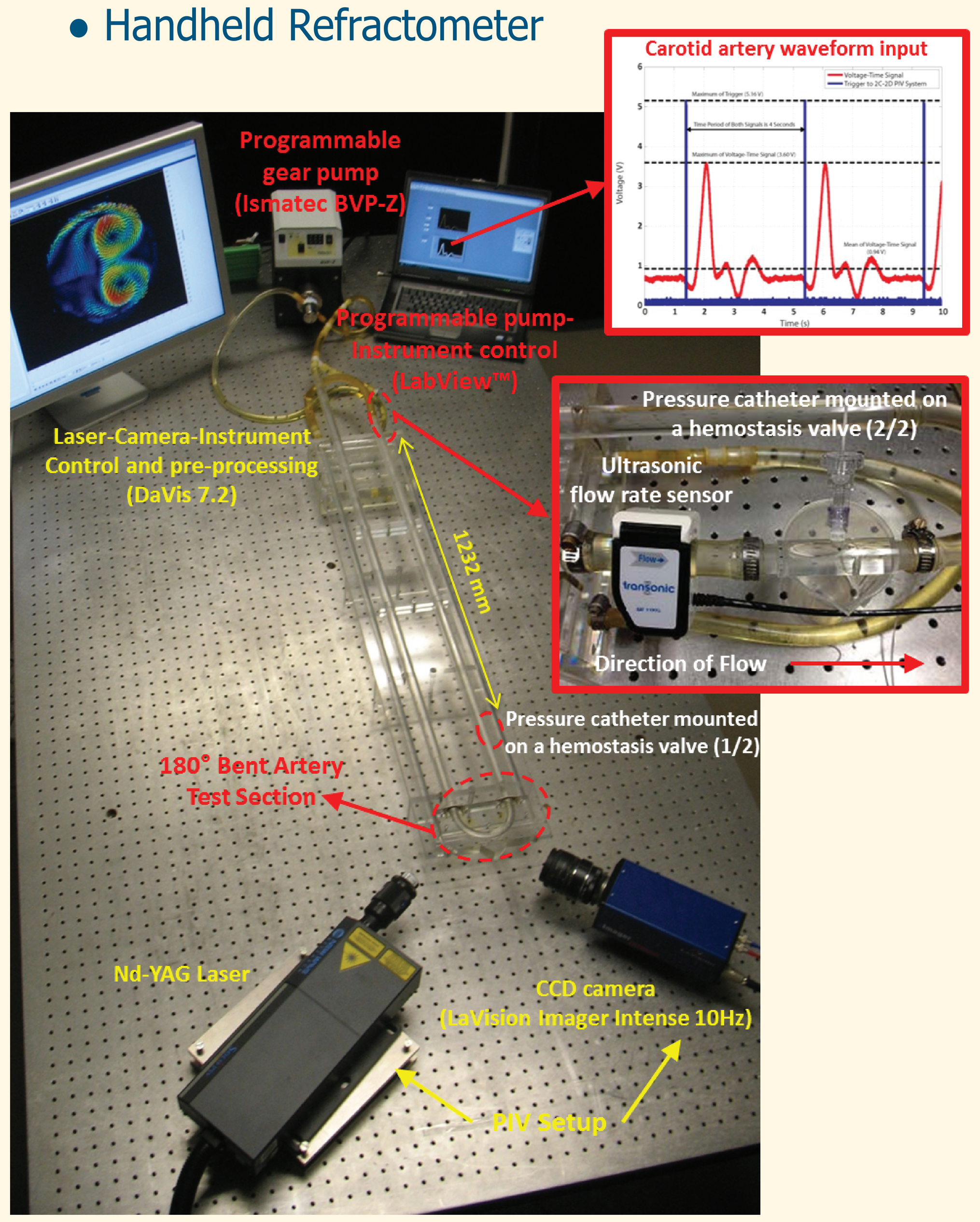


Figure 5: Experimental Setup

Hydrodynamic Measurements

- In 1955, Womersley produced an exact solution of the equations of viscous fluid motion using three main assumptions [7]:
  1. The artery is a straight, circular, rigid tube and arterial expansion is neglected.
  2. The pressure gradient is assumed to be a function of the time only, generated by a pulse wave of finite velocity.
  3. Blood is a viscous, Newtonian fluid with constant density.

Womersley Number: Relationship between unsteady interial forces and viscous forces

$$\alpha = r\left(\frac{\omega\rho}{\mu}\right)^{\frac{1}{2}}$$

α - Womersley Number
r - Radius of artery/pipe
ω - Angular frequency
μ - Dynamic viscosity
ρ - Density

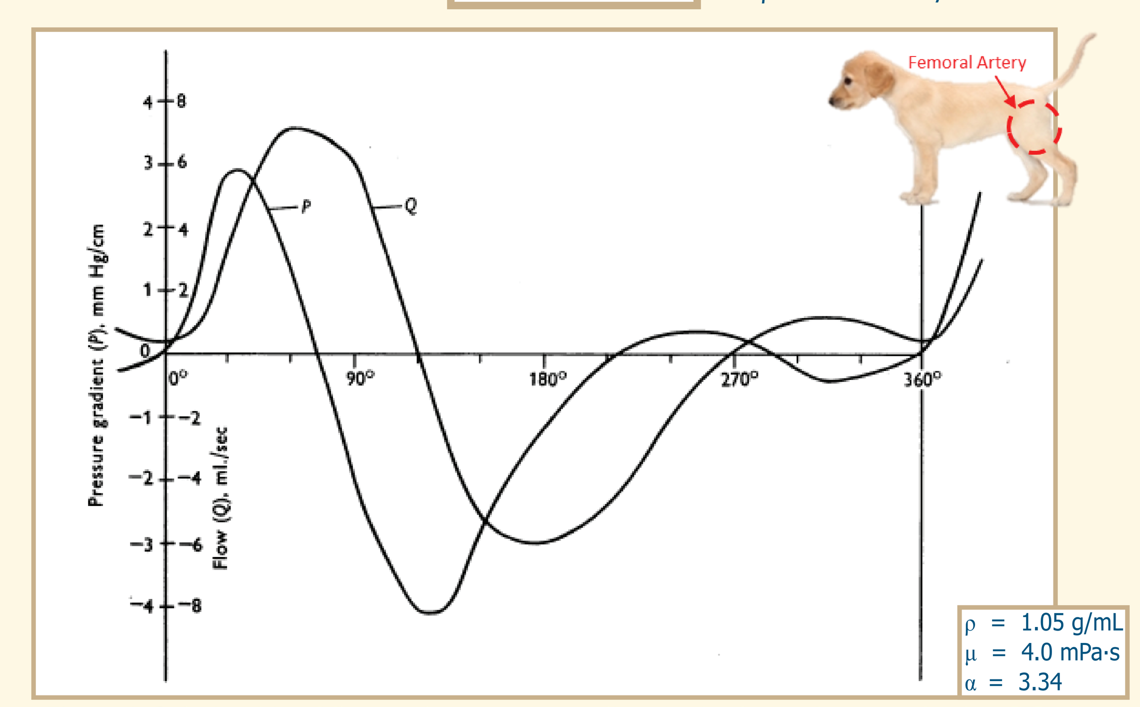


Figure 6: Relationship of flow to the pressure gradient in the femoral artery of a dog. [7]

- Measurements of the pressure gradient were taken on the femoral artery of a dog and the analytical flow rate (Q) showed a phase-lag with the pressure gradient leading the flow rate (Figure 4).

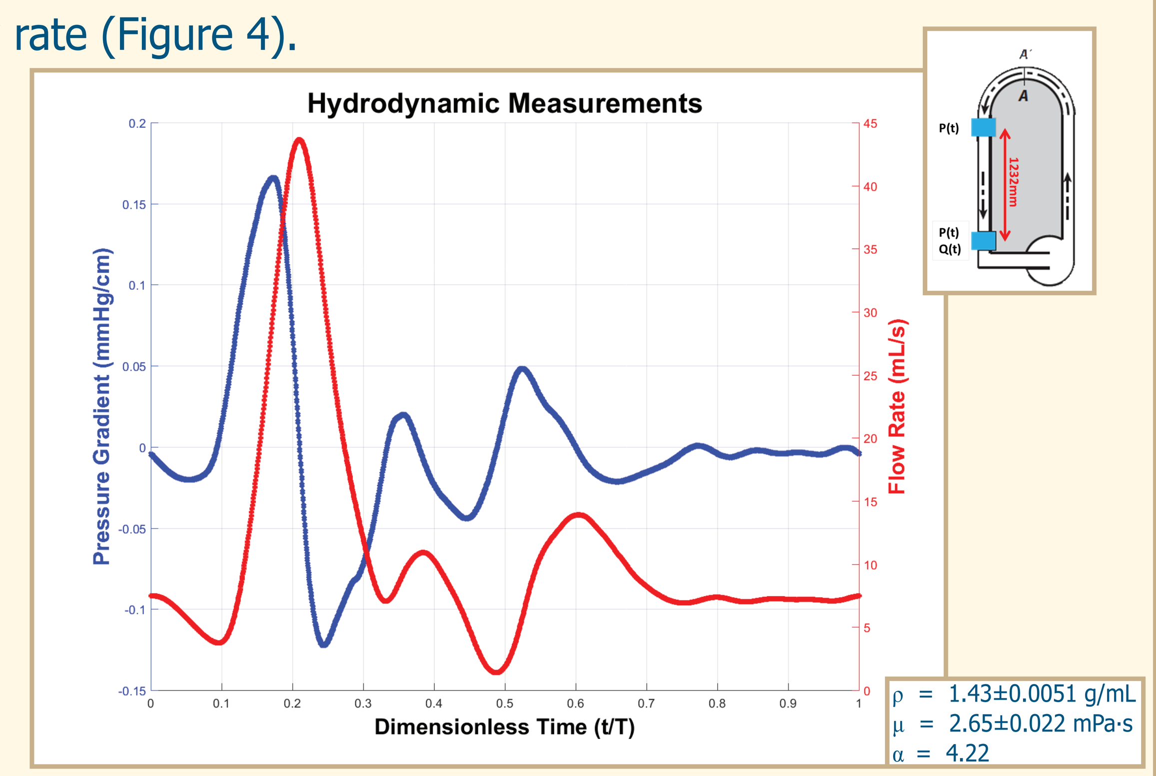


Figure 7: Experimental pressure and flow rate vs. dimensionless time.

- Experimental measurements of the pressure gradient and flow rate (Q) in the 180-degree curved artery model (Figure 5) are illustrative of and similar to the phase-lag seen in the Womersley solution.
- Validation of the experimental data with analytical is in progress. Womersley solution will lead to the characterization of unsteady wall shear stress from the basic hydrodynamic measurements, an indicator of arterial regions prone to blockages.

Fluid Characterization

Rheological Measurements

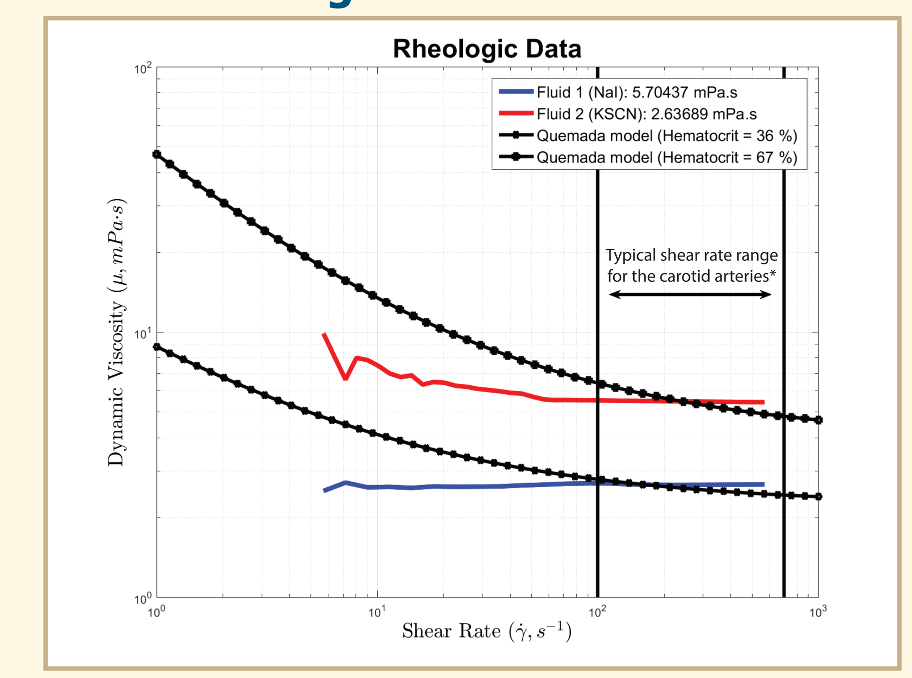


Figure 8: Rheological data for Fluids 1 and 2 with Quemada curves for reference
*Reference: Hoeks, et al., Hypertension. 1995, Jul; 26(1):26-33.

- The Quemada model is a function of hematocrit, the volume fraction of red blood cells (~45% in humans), and shear rate. [8]
- Within the typical shear rate range for the carotid artery, the Quemada model is in fairly good agreement with the experimental data. The fluid data is "flat" within this range, showing typical Newtonian behavior.

Optical Measurements

Fluid 1: NaI-based 1.4932 → Acrylic Test Section 1.481-1.503 ← Fluid 2: KSCN-based 1.4839

Summary & Conclusions

- NaI- and KSCN-based Newtonian blood-analog fluids were created with physiologically appropriate values of viscosity and refractive index, leading to an expected pressure and flow rate relationship.
- Hydrodynamic results can be used to validate the experimental setup via Womersley solution, which can lead to patient specific models and physiological waveforms. This will lead to early detection of diseases like atherosclerosis.

Future Work

- Experiments to characterize the non-Newtonian counterparts of the blood-analog fluids are in progress and are expected to produce different effects near the arterial walls, providing a more realistic representation of arterial blood flow.
- Non-invasive Particle Image Velocimetry (PIV) and Laser Doppler Velocimetry (LDV) measurements are planned to further investigate the effects of the blood-analog fluids in the curved artery test section.

References and Acknowledgements

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