A Kinesthetic Circulatory System Model for Teaching Fluid Dynamics

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Abstract

Previous research has shown that life science students at the University of New England have difficulty applying what they have learned in the physics classroom to concepts of anatomy and physiology, primarily fluid dynamics as they pertain to the circulatory system. To help integrate multiple disciplines into our introductory Physics course, we are developing a kinesthetic circulatory system model. Using this model, this study aimed to improve the students understanding of the equation of continuity, Bernoulli’s and Poiseuille’s principles, hydrostatic pressure, and compliance (elasticity of tubing) as they apply to the cardiovascular system. The impact of this model on improved student understanding of these concepts will be assessed through a combination of pre- and post-test conceptual assessments and open-ended questions. Preliminary studies indicate students had a better perspective for pressure differences due to local (Bernoulli) and global (Poiseuille) conditions.

Objectives

To holistically integrate several fluid dynamics and materials properties into a single kinesthetic circulatory system model in which students develop understanding of the following concepts:

Equation of continuity: Flow rate is constant
Bernoulli’s Principle:
• Static: Pressure change is linear with vertical displacement.
• Dynamic: Pressure change is inversely related to the square of flow speed
Poiseuille’s Principle: Pressure difference due to restricted flow is linear with tube length and inversely as the fourth power of the tube radius.
Compliance: Maintenance of a pressure difference requires major “tubing” (arteries) to be elastic.

Earlier Work

A primitive unidirectional system (below) was deployed in the fluids unit in spring 2013 at UNE. A volunteer audience of 20 general physics students were asked to squeeze two bottle to feel the pressure difference between two pathways and guess why one of the two bottles required greater force to make the fluid flow. All students guessed that the higher pressure pathway was due to a restriction (magnified inset).

The students were also asked to predict what would happen to the fluid speed in the restriction. Conceptually the ideas were confirmed with a Venturi tube demonstration (figure below). Three of the five objectives described at top were examined with this system (continuity, dynamic flow, restricted flow), but only in very qualitative terms. The general student consensus was that these ideas were helpful in supporting their instruction in anatomy and physiology.

Common Preconceptions

• Lack of differentiation between local and global pressure and velocity.
• Lack of differentiation between velocity and flow rate.
• Before content coverage) thinking there is a higher pressure at the restriction.
• Understanding basic concept behind Poiseuille’s Principle before content coverage; reversed their thinking after covering Bernoulli’s Principle.

Kinesthetic Model

The parameters of our circulatory model are:

• The tubing is transparent so fluid flow can be actively observed.
• Fluid speed is visually detectable by neutral density beads mixed into the dyed water.
• Tactile control of the pumping mechanism that respond to flow resistance (either changes of tube radius or compliance of output tube.)
• Tubing of different radius and length to display different fluid dynamics principles.
• Strategically placed valves to highlight different fluid dynamics principles.
• Robust
• Inexpensive.

The plumbing system of various radii and lengths are presented vertically but mounted horizontally to nullify hydrostatic pressure differences.

Pragmatic Considerations

A closed circulatory system has difficulty purging air bubbles and maintaining constant flow rates. The simplest solution is to provide a large, raised, reservoir to keep the system flowing at approximately constant rate depending on the various resistance “R” in the system:

\[ Q = \frac{A}{r^4} \]

The pressure head (\(ΔP\)) is adjustable and controls the flow rate “Q". The total resistance of the tubing is subject to the electrical circuit laws of series and parallel combinations:

\[ \frac{1}{\Delta P} = \frac{1}{\Delta P_1} + \frac{1}{\Delta P_2} \]

Quick change connectors (green circles) are used to swap out different flow resistances that control hydrodynamic and Poiseuille pressure differences.

Measurements

Pressure differences are made with sensitive Vernier barometric pressure sensors. The pump (heart) output force is controlled by pumping into bladder tubing of different elasticity (compliance). Fluid speed is recorded by measuring length travelled in time using a high speed camera. The speeds can be confirmed from flow rate and tube area measurements \(v = Q/A\)

Interview Process

Students were asked to squeeze sphygm pump. The pump is connected to tubing with varying compliance (Young's modulus elasticity) or different restrictions. As the fluid flows through the system the students are asked to observe and record fluid speeds and pressure differences as a function of tube radii, length, and total area of tubing \(ΔA\). Data is graphed according to standard modeling protocol (plotting dependent versus independent variables, linearizing and extracting relevant physics from slopes and intercepts).

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Physics Principles

Equation of Continuity

Conservation of mass states that the flow rate of an ideal fluid (constant density) through a circulatory system that is in a steady state have a constant flow rate:

\[ Q = \frac{dm}{dt} = \frac{dV}{dt} = \text{const} \]

Where \(A\) is the cross sectional area of the tube and \(v\) is the speed of the fluid within the tube.

Bernoulli’s Principle

BP contains hydrostatic and local pressure differences due to hydrodynamic. The static component result in pressure differential due to all the weight of all the fluid above a point in a closed circulation system. Because of conservation of mass, the system results to an acceleration and increased fluid velocity. The Bernoulli equation is as follows:

\[ \Delta P = \frac{1}{2} \rho v^2 \]

Where:

\(ΔP\) = change in LOCAL pressure
\(\rho\) = gravitational field
\(v\) = vertical height difference
\(\rho\) = density of the fluid
\(v\) = LOCAL fluid flow speeds

Poiseuille’s Principle

PP can be used to look at global and local pressure differences that reflect the length and radii of tubing:

\[ \Delta P_{po} = \frac{8A}{r^4} \frac{dQ}{dt} = \frac{1}{r^4} \]

Where:

\(ΔP\) = change in GLOBAL pressure
\(\mu\) = dynamic viscosity
\(L\) = length (as shown in the image)
\(Q\) = volumetric flow rate = \(dV/dt = Av\)
\(v\) = speed of fluid through area \(A\)
\(r\) = radius

Assessment Questions

We will pre and post test students on a series of conceptual questions surrounding the circulatory model. These question include a combination of verbal, graphical, and diagrammatic distractors, such as the example below regarding Bernoulli’s Principle. The above assessment questions along with open ended responses, will be used to evaluate the effectiveness of the kinesthetic model.

Water with air bubbles flows through a pipe that gets wider. In the wider region the water slows down and the bubbles are . . .

• Larger
• Smaller
• Cannot be determined

Conclusions

If this kinesthetic circulatory system model demonstrates enhanced student learning of the basic principles of fluid dynamics, particularly related to anatomy and physiology concepts, additional models should be explored such as:

• Circulatory system diseases – pathophysiology
• Lymphatic system
• Respiratory system
• Urinary system

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References

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