A student practical to conceptualize the importance of Poiseuille’s law and flow control in the cardiovascular system

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INTRODUCTION

Objectives and Overview

The importance of delivering oxygen and removing carbon dioxide in support of tissue metabolism is an easily understood physiological concept for students; however, understanding the underlying concepts of controlling this via tissue perfusion seems less easy to grasp. The concept of driving pressure is something that students grasp relatively easily; however, the role of resistance and its variation in controlling flow and, therefore, the tissue perfusion is more demanding. In this activity, students consider the impact on flow rate of changing pressure or resistance independently. Through answering the guided questions, they develop an understanding of physiological flow control and the impact on oxygen delivery and carbon dioxide removal.

The primary aim of this activity is to improve student understanding of the factors that affect fluid flow and apply them in the context of local flow control in the cardiovascular system. A secondary is to encourage students to generate reproducible data, plot it, and then to take the extra step and interpret the data.

Background

Understanding the factors that govern and control fluid flow within the body has wide-ranging implications in physiology; therefore, a solid understanding of the relationship between pressure, resistance, and flow is essential. It is important to understand what generates flow and what contributes to the resistance to flow.

This laboratory activity centers on the cardiovascular system; however, once the fundamentals are grasped, they can be extended to fluid flow in other systems. The activity assumes flow will be mostly laminar, and the results generated in the laboratory activity correlate well with this assumption.

In the first section of the practical, the students explore the effect of pressure changes on flow rate by altering the height of the liquid column (i.e., generating a head of pressure to induce flow). The principle behind these changes is given by Ohm’s law (or indeed Darcy’s law when considering hydraulic flow):

\[
\text{Flow} = \frac{\text{Pressure gradient}}{\text{Resistance to flow}}
\]

In a single tube (akin to local blood flow), it is quite easily to visualize to what these different terms relate. When applying it to the whole cardiovascular system, cardiac output would be flow, difference between systemic arterial pressure and central venous pressure would be the pressure gradient, and the total peripheral resistance would be the resistance: the underlying principle holds true for both situations.

Having considered the effect of changing pressure on the resulting flow in the first section, the students then complete the remainder of the practical utilizing a reservoir system to maintain a relatively constant head of pressure. This allows student investigation into some of the factors that generate resistance to flow in a tube. These factors are highlighted by looking at Poiseuille’s law, which can be viewed in a similar format to Ohm’s law:

\[
\text{Flow} = \frac{\text{Pressure gradient} \times \pi \times (\text{tube radius})^4}{8 \times \text{Length of tube} \times \text{Fluid viscosity}}
\]

All of the experiments in this activity use the same liquid (tap water), and, whereas fluid viscosity is an important physiological consideration, it is not investigated at this stage. In the first of these activities, the length of the tube is varied, utilizing four different lengths of tubing connected to the system. In the next, the effect of radius is explored using three different sizes of glass capillary tubes. These activities use individual tubes to
investigate the effect of tube length and radius in changing resistance to flow. In the final experiment, the students are asked to investigate the effect of changing the number of tubes in parallel so that they can relate it to a branching network, as seen in the cardiovascular system. This allows consideration of multiple resistances arranged in parallel, reducing the total resistance, as seen below:

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots + \frac{1}{R_n}$$

Throughout the activities, the students actually record the time taken (in seconds) to collect a known volume of water (5 mL). They are then asked to manipulate these data to calculate a flow rate (in mL/s) and repeat the measurements three times. This allows a mean flow rate to be calculated, as well as an opportunity to discuss sources of variability. The mean flow rate (in mL/s) acts as the dependent variable, and students observe how this changes, depending on differences in fluid height, tube diameter, tube length, and tube number.

A more comprehensive experimental approach focusing on hemodynamics was described by Pontiga and Gaytán (5) that took into consideration both the Bernoulli equation (velocity effects on pressure) and Reynolds number (likelihood of turbulence); however, a data acquisition system was required that potentially limits its more widespread adoption. A systemic approach utilizing pumps and multiple vascular beds was recently published by Washburn and Stewart (6), which attempts to overcome the hurdle of students thinking in an integrative physiology manner and does not focus on Poiseuille’s law per se.

This laboratory practical was developed to encourage students to generate reproducible data, plot it, and then to take the extra step and interpret the data. In our experience, this final step of interpreting data is a hurdle for many students. The incorporation of a student-led, small-group teaching (SGT) session after the practical allows the concepts to be explored further and feedback to be given to any areas of uncertainty, including areas of data handling. This session also allows exploration of new general scientific concepts, such as the origin of experimental errors when students do not get exactly the same answer.

For example, the SGT session may extend into discussing the large changes in muscle blood flow to support metabolism during dynamic exercise while arterial blood pressure (ABP) remains relatively normal. Linking these resistance changes to O₂ delivery and CO₂ removal can be grasped more easily if the factors controlling vascular resistance are understood.

**Learning Objective**

The wider learning objective for this practical session is to help students understand the physiological control of fluid flow in the body.

**Learning Outcomes**

After the practical session, a follow-up SGT session is held to discuss the results obtained. At the end of both sessions, the students should be able to:

1. Determine the effect of changing different physical variables on fluid flow rate.
2. Discuss the likelihood that each variable is a common mechanism for physiological control of flow and understand the relative importance on a systemic or local level.
3. Consider these variables in the context of Poiseuille’s law.
4. Appreciate sources of experimental errors and the need for repeat measurements.
5. Interpret empirically derived data qualitatively and quantitatively to reinforce their learning.

**Activity Level**

This practical has been developed and used in year 1 cardiovascular physiology modules on both Biomedical Science and Biomedical Materials Science at the University of Birmingham. The former program has an intake of up to 200 students, whereas the latter has an intake of up to 30 students. Anecdotally, the Materials Science students tend to be more comfortable with mathematical approaches and using physics to understand phenomena, whereas the Biomedical Science students tend to be more comfortable with the physiology and less so with the mathematics and physics. The optimum allocation of students to each setup is three: one student to record times on the stopwatch, one to release/apply the clamp, and one to monitor when the volumetric flask contains exactly 5 mL of water. Once the equipment is laid out before the class, the students are able to swap between the experiments independently and at their own pace.

**Prerequisite Student Knowledge**

The format of the practical does not require any prior knowledge of physiological processes, as it is based on empirical observations; however, we recommend that the basic structure of the cardiovascular system be taught before the activity (definitely before embarking on the SGT session after the activity). This allows students to consider how pressure is generated and what vessels constitute the main sites of resistance. Basic data manipulation and interpretation skills are required to plot the data and draw conclusions from it.

**Time Required**

This practical can be completed within a single 90-min session, which includes time for the students to plot the relevant graphs and have peer discussions around the interpretation and the associated questions.

**MATERIALS AND METHODS**

**Equipment**

The equipment was made in house at the University of Birmingham by the teaching laboratory technicians using standard items of laboratory equipment. All items can be purchased at low cost, making it easy to deploy in any teaching setting. Once constructed, the flow modules can be stored easily and reused multiple times. Detailed description of the equipment requiring purchase and of how to build the different flow modules can be found in the Supplemental Data. (All supplemental material is available at https://dx.doi.org/10.6084/m9.figshare.12594554.) Briefly, for investigating the effect of pressure (height of a column of liquid), all that was required was a 50-mL burette with a small length of rubber tubing fixed to the bottom on which a clamp could be fitted to start/stop the flow of water (see Fig. 1). Effluent was collected in a beaker, and a stopwatch was used to

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measure how long it took for 5 mL of liquid to flow out. For the subsequent sections of the practical, a 25-mL burette was used, and the top was connected via rubber tubing to a 5-liter reservoir placed on the shelving above the bench. The tubing at the base could then be connected to the different flow modules that comprised the different configurations of tubes to be tested.

Experiments

Experiment 1: The effect of column height on flow rate. The steps for experiment 1 are as follows:
1. Set up the equipment for this experiment using the 50-mL burette provided (see Fig. 1A) and then fill the burette with water (using the 50-mL syringe provided). Ensure the clamp is closed initially.
2. Release the clamp and, using the stopwatch provided, measure the time taken for 5 mL of water to be collected, starting from predetermined set levels [e.g., full (50–45 mL), half full (30–25 mL), and nearly empty (10–5 mL)]. Take each measurement three times to ensure consistency.
3. Use the results to calculate a mean flow rate (mL/s) for each column height.
4. Plot your results (see Fig. 1B) to assess the relationship between column height and flow rate. Think about which is the independent variable when plotting your results.
5. Discuss your results with your peers, and answer the related questions (see Table 1).

Experiment 2: The effect of tubing length. The steps for experiment 2 are as follows:
1. Set up the equipment for this section using the 25-mL burette and water reservoir (to maintain a constant pressure), as shown in Fig. 2A. Ensure the clamp is closed initially.
2. Release the clamp and, using the stopwatch provided, measure the time taken to dispense 5 mL of water to be collected into a 5-mL volumetric flask through the different lengths of capillary tubes. Take each measurement four times and discard the first measurement (as this is flushing the system) to ensure consistency.
3. Use the results to calculate a mean flow rate (mL/s) for each tube length.
4. Plot your results (see Fig. 2B) to assess the relationship between length of tube and flow rate. Think about which is the independent variable when plotting your results.
5. Discuss your results with your peers, and answer the related questions (see Table 1).

Experiment 3: The effect of tube radius. The steps for experiment 3 are as follows:
1. Set up the equipment for this section using the 25-mL burette and water reservoir (to maintain a constant pressure), as described in experiment 2. Swap the “tube length” module for the “tube radius” module, as shown in Fig. 3A. Ensure the clamp is closed initially.
2. Release the clamp and, using the stopwatch provided, measure the time taken to dispense 5 mL of water to be collected into a 5-mL volumetric flask through the different diameter capillary tubes. Take each measurement four times and discard the first measurement (as this is flushing the system) to ensure consistency.
3. Use the results to calculate a mean flow rate (mL/s) for each tube radius. Note: You are given the tube diameters but asked to calculate results in terms of the radius.
4. Plot your results (see Fig. 3B) to assess the relationship between radius (r) of tube and flow rate. In addition, plot the relationship between \( r^2 \) and flow rate. Think about which is the independent variable when plotting your results.
5. Discuss your results with your peers, and answer the related questions (see Table 1).

Fig. 1. The effect of pressure on flow rate. A: a clamp is attached to the rubber tubing, allowing the 50-mL burette to be filled by the syringe. The linear scale on the burette allows recording of the time taken for 5 mL to flow out at different column heights (pressures) when the clamp is released. The codes in parentheses refer to the construction details in the Supplemental Data. B: the calculated flow rate can be plotted against the column height (pressure can be substituted for height once the questions in Table 1 are answered).
Table 1. Questions and answers related to each experiment

| Question | Answer/Discussion Topic |
|----------|-------------------------|
| What physical variable is changing with the column height? | Experiment 1: Pressure. The pressure in a column of liquid is given by height density \times gravity. (The discussion can be widened here to consider units of pressure and why we use mmHg to measure blood pressure.) |
| What does this relate to in the cardiovascular system, and is it something that can change? How? | Arterial blood pressure (ABP). Yes this can vary. (The discussion can then bring in the fact that ABP relies on the relationship with cardiac output and total peripheral resistance.) |
| What would be the implications for our ability to control blood flow to different tissues, if this were the only control mechanism available? | Flow would increase with ABP (assuming all other factors were constant). If driving pressure were the only control mechanism, it would imply that there was no ability to differentially control flow in different tissues. (The discussion can be extended here to consider whether there is a need for differential control of blood flow to different tissues and why.) |
| Based on the conclusions you made above, would this be an efficient way for us to control blood flow to different tissues? | Not efficient at all, as blood flow could not be regulated to tissues with differing metabolic needs. |
| Would you expect the length of blood vessels to change in the body as a means of controlling flow? Comment on your answer. | Experiment 2: Changing path length is not an expected mechanism to control flow under normal physiological circumstances. (The discussion here could consider acute path length changes, such as anastomoses, or chronic path length changes, such as angiogenesis.) |
| Is this likely to be a common mechanism for controlling blood flow to different tissues? | Unlikely to be a common mechanism for acute control. However, examples exist where acute path length changes occur, such as in skin and thermoregulation. (The discussion here could have angiogenesis, both physiologically (exercise) or pathologically (tumor growth), and why it occurs.) |
| Which graph allows for blood flow to be controlled in a linear fashion? | Experiment 3: Flow changes linearly with the plot of \( r^4 \) rather than \( r \) itself. (Experimental errors/variability can sometimes mask the result. So, a discussion can be had on what the expected flow rate would be if \( r = 0 \). Using the origin as an extra point allows the shape to be more easily seen.) |
| Is the radius a variable that is likely to change to control blood flow to different tissues? How? | Yes. This is the concept of vasoconstriction and vasodilation. (The discussion here can be expanded into considering mechanisms of vasoconstriction and vasodilation.) |
| What are the implications for the control of blood flow if it is proportional to the fourth power of a variable? | Efficiency. Only relatively small changes in radius are required to induce significant changes in flow. |
| Which variable is the addition of more tubes in parallel affecting? | Experiment 4: Resistance. Adding resistances in parallel reduces the total resistance in that section. (The discussion here could compare resistances in series vs. parallel.) |
| What are the benefits to the tissue of having more blood vessels in parallel? | Increasing blood vessel density within a tissue with more branching and vessels in parallel. This will reduduce diffusion distance and so is beneficial. (The discussion here could consider results from experiment 3 in addition to experiment 4. More vessels in parallel would reduce total resistance, and so to keep the total resistance constant, a smaller radius (increased tone) would be required.) |

Following completion of each experiment, the students were asked to discuss some questions with their peers and provide answers. These answers were then used by the tutor to form the basis of group discussions in the small-group teaching session that followed the laboratory practical.

**Experiment 4: The effect of tubes in parallel.** The steps for experiment 4 are as follows:

1. Set up the equipment for this section using the 25-mL burette and water reservoir (to maintain a constant pressure), as described in experiment 3. Swap the “tube radius” module for the “tubes in parallel” module, as shown in Fig. 4A. Ensure the clamp is closed initially.
2. Release the clamp and, using the stopwatch provided, measure the time taken to dispense 5 mL of water to be collected into a 5-mL volumetric flask through the different number of capillary tubes arranged in parallel. Take each measurement four times and discard the first measurement (as this is flushing the system) to ensure consistency.
3. Use the results to calculate a mean flow rate (mL/s) for each number of tubes arranged in parallel. Note: This module consists of a single tube or up to five tubes arranged in parallel, with all tubes having the same diameter.
4. Plot your results (see Fig. 4B) to assess the relationship between the number of tubes in parallel and flow rate. In addition, plot the relationship between flow rate and the reciprocal of the number of tubes (i.e., 1/number of tubes). Think about which is the independent variable when plotting your results.
5. Discuss your results with your peers, and answer the related questions (see Table 1).

**Expected Results**

**Experiment 1: The effect of column height on flow rate.** Students should expect to record times that are quite consistent for each column height, providing that close attention is paid to the water level and starting/stopping the stopwatch. As the column height reduces, the time taken to collect 5 mL of liquid increases, and so the calculated flow rate reduces with the column height. The students should see this relationship clearly when plotted with flow rate as the dependent variable (see Fig. 1B).

**Experiment 2: The effect of tubing length.** Students should observe that the time required to collect 5 mL of liquid increased with the length of tube used. The relationship can be visualized when the data are plotted with tube length as the independent variable (see Fig. 2B).

**Experiment 3: The effect of tube radius.** As the diameter of the capillary tube increases, the student should see that the time taken to...
collect 5 mL of liquid decreases. Therefore, in their calculations and on the plotted graphs, they should see that flow rate increases with diameter. The students are asked to plot these data, and they should observe that the response is not linear with changes in $r$. They are also asked to plot the data with $r^4$ as the independent variable to investigate the power relationship between flow and radius (see Fig. 3B).

**Experiment 4: The effect of tubes in parallel.** Students should observe that the flow rate increases as the number of parallel tubes increases. The students are asked to plot the flow rate against the number of tubes in parallel and observe that the relationship is not linear. When they plot the flow rate against the reciprocal of the tube number, they can then interpret the data accordingly (see Fig. 4B).
Troubleshooting

The experimental setup is quite robust and gives reproducible results; however, when results are variable, there is usually a simple explanation. The flow rates can vary between individual student

Fig. 3. The effect of radius on flow rate. A: the fluid reservoir is placed on top of the bench to give a pressure head. This is connected to the flow module by rubber tubing with a clamp on it. A 5-mL volumetric flask is used to collect fluid, and the time taken with different diameter tubes is recorded on a stopwatch. The codes in parentheses refer to the construction details in the Supplemental Data. B: the calculated flow rate plotted against the tube radius ($r$) as well as against $r^4$. The interpretation of the results is made in conjunction with the questions in Table 1.

Fig. 4. The effect of parallel tubes on flow rate. A: the fluid reservoir is placed on top of the bench (shown in Fig. 3) to give a pressure head. This is connected to the flow module by rubber tubing with a clamp on it. A 5-mL volumetric flask is used to collect fluid, and the time taken with different numbers of tubes in parallel is recorded on a stopwatch. The codes in parentheses refer to the construction details in the Supplemental Data. B: the calculated flow rate plotted against the number of tubes. The interpretation of the results is made in conjunction with the questions in Table 1.

**Troubleshooting**

The experimental setup is quite robust and gives reproducible results; however, when results are variable, there is usually a simple explanation. The flow rates can vary between individual student
setups, and this usually is the result of the individual manufacture of each setup. This is difficult to overcome due to the bespoke nature of each flow module. Commercial manufacture with reduced tolerances would improve this; however, the relationship between the changed variables within each setup usually gives consistent data to plot and adequately interpret the effect of changing it. When students get inconsistent readings internally, it is usually because they have not followed the protocol closely (e.g., in experiments 2–4 they have neglected to discard the first result and use the next three results for consistency). If any airlocks are removed in the first data collection, as described in the protocol, then the data are usually less variable. Overall, if the students follow the protocols given to them, then the data generated can be plotted successfully and allow the students to understand how that variable affects fluid flow.

Postpractical SGT Session

At the end of each experiment, the students are asked to consider some focused questions pertaining to each experimental condition and how it applies to the cardiovascular system. These questions, alongside their data plots, form the basis of a subsequent small-group session, where they can explore the significance of the results and apply them to cardiovascular physiology. The questions for each experiment and suggested answers/discussion topics are shown in Table 1. The questions are designed to guide the student into considering how different variables affect flow and whether each is likely to be a common mechanism for physiological control of flow.

After the discussion of each individual experiment, and the implications of the effect of that physical variable on flow rate, the students are asked to bring the results together from experiments 1–3 by concluding what factors are proportional and which are inversely proportional with relation to the flow rate. This aids the students in beginning to understand the core concept of Poiseuille’s law. Importantly, they also grasp the concept that, just because a variable can cause a change, it does not necessarily mean that it has that physiological role.

The final question and discussion point that draws together all of the empirical data and its physiological application to the cardiovascular system is, “Using all of the information that you have put together, comment on how you think blood flow to individual tissues can be regulated without affecting other organs.” In discussing this question, it is useful to get the students to consider vasoconstriction/vasodilation controlling local resistance and flow to determine distribution of cardiac output, while remembering the relationship of cardiac output and total peripheral resistance to generate the driving pressure in the first place.

Limitations/Adaptations

This laboratory practical was designed to use common consumable equipment found in the laboratory or easily purchased. The low cost and easy availability make this practical ideal to deploy in any institution. Since it was custom made by the laboratory technicians, there was some initial trial and error during development; however, the instructions given in the Supplemental Data are the result of this development and give reliable and reproducible data.

In experiment 1, some students were unsure of the relationship between height/depth of liquid and pressure (often because they had not studied or had forgotten the physics). However, these students intuitively grasped that, as a diver or submarine went deeper underwater, then the pressure increased. Therefore, it was a small step for them to conclude that the column height was a proxy for the driving pressure to generate the flow.

In experiments 2–4, the reservoir was used to create a constant driving pressure (since the effect of pressure changes had been explored in experiment 1). This was achieved by having a fluid volume that was sufficiently large that the level did not significantly fall during each experiment.

In experiment 3, if students were unable to appreciate the curved nature of the radius versus flow plot, then encourage them to consider what happens if the radius continued to get smaller and smaller until it was at zero. This gave them a “free” data point to plot.

This practical allows the students to see the effects on flow of changing a single factor. However, it must be remembered that the fluid is water and so not perfectly representative of blood. Viscosity was not considered in this practical and is not likely to be a big factor in acute control of flow; however, it could become important in pathologies such as polycythemia. If required, the practical could be extended to using the same equipment with fluids of different viscosities.

Flow is not always laminar in the cardiovascular system and so not perfectly described by Poiseuille’s law. The experimental results and errors demonstrate that it correlates to a mostly laminar flow pattern that is reproducible and helps students understand the principles involved. At this learning stage, it is not necessary to go into turbulent flow for the qualitative understanding and interpretation of physiological control. These additional considerations are built on in a second-year module when hematology is covered in more detail and viscosity and flow patterns can be appreciated more fully.

Conclusions

Investigating the individual factors that control fluid flow in a tube in an in vitro situation allows the student to dissect out the complexity of flow control in the cardiovascular system. This activity tackles some of the identified core principles in physiology, such as “flow down gradients” and “interdependence” (4). By having these building blocks in place, they are in a stronger position to understand physiological phenomena, such as changes in vascular tone, as well as the effect of vessel recruitment during higher flow conditions. Introducing these concepts in a laboratory practical helps bring the theory to life and allows students to more easily apply the knowledge (3). In addition to the application of the empirical data to the cardiovascular system, there are other important generic scientific learning outcomes to be gained; for example, the need to carry out replicates and the sources of variability and how they might influence where a regression line might be plotted. It is human nature to believe what you see, and these experiments and discussions allow for more complex integrated responses to be introduced and for the students to be able to look forward to them, if they were not taught at that time. The questions incorporated in this laboratory activity are worded so that the instructors can develop to the level appropriate for their student group. For example, the students might consider the integrated cardiovascular response to exercise with changes in vascular resistance being dependent on vascular bed and allowing control of cardiac output distribution, and, additionally, how cardiac output is increased in the face of a fall in peripheral resistance, such that ABP does not fall precipitously and affect cerebral or renal blood flow. A further extension of the concept would be for students to remember that the experiments relate to fluid movement, and so this includes gases. Thus these principles can be applied equally to the respiratory system with regard to bronchoconstriction and dilation. Integrative physiology is acknowledged to be difficult for students to grasp; however, this approach provides a firm foundation for them to build on. In summary, this laboratory practical is a very cost-effective way of getting students to investigate the underlying principles behind the control of blood flow in the body.

Additional Resources

For additional information on this topic, please see Badeer (1) or Belloni (2) for discussions on the principles of hemodynamics from the aspect of the governing equations. Additionally, Pontiga and Gaytán (5) provide a comprehensive description of an experimental approach connected to a computer recording system.
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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

A.C. conceived and designed research; A.C. performed experiments; A.C. analyzed data; A.H., C.J.R., P.K., and A.C. interpreted results of experiments; A.C. prepared figures; A.C. drafted manuscript; A.H., C.J.R., P.K., and A.C. edited and revised manuscript; A.H., C.J.R., P.K.; A.C. approved final version of manuscript.

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