A simple model to demonstrate perfusion and diffusion limitation of gases

Praghalathan Kanthakumar and Vinay Oommen
Department of Physiology, Christian Medical College, Vellore, Tamil Nadu, India

Submitted 29 May 2012; accepted in final form 27 August 2012

Transfer of gases across the respiratory membrane is limited by either perfusion or diffusion (1). This concept is usually explained in terms of whether a gas reaches its partial pressure equilibrium in the pulmonary capillaries. If it does, the gas is considered to be “perfusion limited,” and if it does not, it is considered to be “diffusion limited.” To facilitate the understanding of this concept, we designed an analogical model using paper cups and water to simulate the physiological principles behind gas transport.

Materials and Methods

Materials Required

The following materials are required: paper cups (~200-ml volume), a long frame on which to stick the paper cups (this should be able to hold the weight of the cups filled with water), instant glue, and a sink with a tap where the experiment is to be performed.

Construction of the Model

Ten identical paper cups were stuck on a plastic wire casing ~2 in. wide and 40 in. long using instant glue. Sufficient space was given between the cups to prevent water overflowing from one cup to another. The final assembled model is shown in Fig. 1A.

Physiological Basis

In this analogy, each cup stood for the capacity of the blood for the gas at its alveolar partial pressure. The capacity of the blood for a gas includes dissolved gas as well as other forms, such as bound to hemoglobin. The demonstration of diffusion limitation used oxygen as the example, whereas the demonstration of diffusion limitation used carbon monoxide (CO) as the example. These gases were chosen as they have nearly identical solubility coefficients and both bind to hemoglobin. For both gases, the hemoglobin-bound form is the major determinant of the total gas content in the blood. This enabled the use of similarly sized paper cups in this analogy.

The speed at which the cups were moved stood for the perfusion rate. The flow of water through the tap was equivalent to the diffusion of a gas across the respiratory membrane (Fig. 1B). Cups filled up to the brim were equivalent to the pulmonary capillary partial pressure of the gas reaching its equilibrium with alveolar air.

Results

Presentation of the Model

This model was presented to first-year medical students in groups of 15 students. Students were first shown the model, and the components of the model were then explained. Students were told that the cups would be positioned under a running tap and moved at a constant speed.

Two volunteers from each group were asked to perform the experiment in front of the others. While one student timed the process, the other student moved the cups under the running tap. The experiment was conducted in an area where the sink had sufficient space to maneuver the setup.

Two experiments were conducted. The first experiment was designed to convey the physiological principles underlying oxygen transfer that make it “perfusion limited.” The second experiment was designed to simulate the physiological factors that make CO transfer “diffusion limited.”

At the start, students were given a set of instructions to perform the experiment. A set of questions was discussed during each experiment.

Experiment 1: model of oxygen transfer across the respiratory membrane. Students were given written instructions to fill the water cups to approximately three-quarters of their capacity. They were to adjust the water flow through the tap such that the remaining volume filled in ~4 s. While one student moved the cups, the other student told the first student when to do so. The first cup was placed under the tap for 12 s. After 12 s had elapsed, the next cup was to be brought under the tap. This continued for 60 s (Fig. 2A).

The questions given to aid the discussion were as follows:

- Why were the cups three-quarters full at the beginning of the experiment?
- Why does one wait for 12 s even though the time taken for the cups to fill was only 4 s?
- Would increasing the speed at which the cups were moved increase the amount of water collected in a given time? [Students were instructed to repeat the experiment by increasing the speed of cup movement to one cup every 6 s instead of 12 s (Fig. 2B).]
- Would increasing the water flow through the tap increase the amount of water collected in a given time? [Students were asked to repeat the experiment with the normal speed of cup movement and a higher water flow (Fig. 2C).]
- What limited the amount of water carried in a given time in the above experiment and what was the physiological equivalent of this factor?

It was explained to the students that the mixed venous blood having a P02 of 40 mmHg is ~75% saturated with oxygen. Therefore, the cups that stood for the oxygen carrying capacity of the blood at 100 mmHg (alveolar P02) were three-fourths full at the beginning of the experiment. (At this point, the contribution of dissolved and hemoglobin-bound forms of oxygen can be introduced to the students. Pulmonary capillary P02 is determined by the dissolved form. The difference in partial pressures between the alveoli and capillaries is one of the factors that determine the rate of diffusion. However, the dissolved form contributes very little to total oxygen carrying capacity. The oxygen carrying capacity is nearly equal to the amount of oxygen bound to hemoglobin.)
Students were instructed to use empty water cups for the rate of perfusion, this was explained as a model of "rate of cup movement." As the rate of cup movement stood did not. Therefore, the limiting factor was identified as the water collected, but increasing the water flow through the tap was more overflow of water. At the end of 1 min, only five cups were full. The total amount of water collected did not increase (Fig. 2B).

When only the flow of water was increased with the rate of movement of the cups kept constant, students noticed that there was more overflow of water. At the end of 1 min, only five cups were full. The total amount of water collected did not increase (Fig. 2B).

Increasing the rate of cup movement increased the amount of water collected, but increasing the water flow through the tap did not. Therefore, the limiting factor was identified as the "rate of cup movement." As the rate of cup movement stood for the rate of perfusion, this was explained as a model of perfusion limitation.

Experiment 2: model of CO transfer across the respiratory membrane. Students were instructed to use empty water cups for this experiment. The water flow through the tap was adjusted such that each cup filled in ~30 s. One student held the row of cups while another student timed the process. The first cup was to be placed under the tap for 12 s. After 12 s had elapsed, the next cup was positioned under the tap. This was repeated for 1 min (Fig. 2A).

The questions given to aid the discussion were as follows:

1. Why were the cups empty at the beginning of the experiment as opposed to the earlier experiment?
2. Why was the water flow through the tap set at a low flow?
3. Would increasing the speed at which the cups were moved increase the amount of water collected in a given time? [Students were asked to repeat the experiment by increasing the speed of cup movement, once every 6 s, and note the amount of water collected (Fig. 3B).]
4. Would increasing the water flow through the tap increase the amount of water collected in a given time? [Students were asked to repeat the experiment with the normal speed of cup movement and a higher water flow (Fig. 3C).]
5. What limited the amount of water carried in a given time in this experiment and what was the physiological equivalent of this factor?

It was explained to the students that the capacity of the blood to carry CO was shown by the volume of the cups. As CO can displace oxygen from hemoglobin, all the hemoglobin molecules are available for CO to bind. Therefore, the cups that were moved under the tap were empty. (At this point, students can be reminded of the fact that as in the case of oxygen, the hemoglobin-bound form of CO is the major contributor to the...
In our model, the water flow representing oxygen diffusion was kept at one cup every 12 s and the flow representing CO diffusion was kept lower, at one cup every 30 s. However, physiologically, the CO diffusion rate is proportionately much lower considering the low partial pressures of CO used in diffusion studies. To accurately reflect this would have required a very low water flow, which was not practical.

The rate of diffusion in our model was represented by the flow of water through the tap. Equilibrium of partial pressures is represented by a full cup, after which water overflows. In the lungs, however, the rate of diffusion keeps decreasing as the partial pressure equilibrium is approached due to a decreasing partial pressure gradient, until it stops at equilibrium. Ideally, to model this, the flow of water through the tap should gradually decrease as the cup fills and stop once the cup is full. This can be modeled using a siphon and a water reservoir, but the design would be complex and the time to fill each cup would be very long.

This model specifically focuses on the concepts of diffusion and perfusion limitation of gases in the lung. Care must be increased the water flow through the tap did. Therefore, the factor that limited the amount of water collected was the “flow of water through the tap.” This was analogous to the diffusion of a gas across the respiratory membrane. Hence, this model simulates the diffusion limitation of a gas.

**DISCUSSION**

Both the experiments described above were designed to incorporate different physiological factors that, under normal circumstances, make oxygen perfusion limited and CO diffusion limited. It was also emphasized that although oxygen transfer is known to be perfusion limited and CO is known to be diffusion limited, these are not intrinsic properties of the gases themselves.

The factors that make oxygen perfusion limited that were modeled were as follows:

1. A high rate of diffusion as a result of a large partial pressure difference. This was modeled using a higher water flow as opposed to that of CO.
2. A lower capacity of the blood to bind new oxygen (compared with CO) as hemoglobin is 75% saturated with oxygen in the mixed venous blood. This was modeled using empty cups.

The factors that make CO diffusion limited that were modeled were as follows:

1. A low rate of diffusion due to a low concentration of the gas, such as used in diffusion studies. This was modeled using a low water flow compared with that of oxygen.
2. A high capacity of the blood to bind CO, as CO can easily displace oxygen from hemoglobin due to its high affinity. This was modeled using empty cups.

This model can also be used to illustrate the behavior of gases, such as nitrous oxide, that do not bind to hemoglobin. However, in this case, it must be clearly emphasized to students that the volume of the cup, which represents the gas carrying capacity at the alveolar partial pressure, mainly consists of the gas in the dissolved form.

**Limitations**

In our model, the water flow representing oxygen diffusion was kept at one cup every 12 s and the flow representing CO diffusion was kept lower, at one cup every 30 s. However, physiologically, the CO diffusion rate is proportionately much lower considering the low partial pressures of CO used in diffusion studies. To accurately reflect this would have required a very low water flow, which was not practical.

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This model specifically focuses on the concepts of diffusion and perfusion limitation of gases in the lung. Care must be
taken while integrating this model with other aspects of respiratory physiology.

Conclusions

The model described above can be constructed in a short time, using materials that are inexpensive, and the experiments can be done in any place having a tap and a sink. The experiments enabled the students understand the concept of diffusion and perfusion limitation of gases easily. Apart from imparting an intuitive understanding of this concept, this experiment also served to reinforce other physiological principles such as the oxygen-hemoglobin dissociation curve, partial pressure of gases, factors that govern the diffusion rates of gases, and the pathophysiology of CO poisoning.

We believe that this experiment simplifies the concept of perfusion and diffusion limitation of gases, which is otherwise a difficult concept for medical students.

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

AUTHOR CONTRIBUTIONS

Author contributions: P.K. and V.T.O. conception and design of research; P.K. and V.T.O. performed experiments; P.K. and V.T.O. prepared figures; P.K. drafted manuscript; P.K. and V.T.O. edited and revised manuscript; P.K. and V.T.O. approved final version of manuscript.

REFERENCE