Use of analogies in the study of diffusion

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Emergent processes, such as diffusion, are considered more difficult to understand than direct processes (3). In physiology, most processes are presented as direct processes, so emergent processes, when encountered, are even more difficult to understand. It has been suggested that, when studying diffusion, misconceptions about random processes are the principal cause of this difficulty (5). While general diffusion, membrane diffusion, and diffusion rate expressed by Fick’s law are covered in numerous physiology textbooks (1, 2, 4, 6, 7, 9–11), parameters that result from the kinetic theory of gasses are mentioned only partially and briefly in some of them (6, 11). Communication with students, however, has revealed that their understanding of these parameters is often thwarted by an erroneous and, indeed, frequently nonexistent conceptual framework for the behavior of matter at a molecular level. To help students form a useful picture of diffusion and to correct misconceptions about molecular level processes, velocity, the rate of collisions, and the number of interacting molecules are presented to them in the form of analogies. Analogies are used because few students are familiar with physical quantities and conversion of units or well versed in quantitative reasoning. So, analogies link quantities that are abstract and lacking in real meaning for the majority of students with something that is hopefully more familiar to them. In this way, it is expected that knowledge of these parameters and familiarization with them through analogies will lead students to understand that the macroscopic transport of matter through diffusion is a consequence of the immense number of movements in all directions and the equally immense number of collisions.

The velocities of small molecules in air, including water molecules, reach several hundred meters per second at room temperatures, which, when expressed in kilometers per hour, amounts to 1,000–2,000 km/h, meaning that molecules move as fast as fighter jets or shotgun bullets. It is only when velocities are expressed in kilometers per hour that students seem to become aware of how great the speeds of molecules actually are. Due to the equipartition law, the mean kinetic energies \((mv^2/2)\), where \(m\) is mass and \(v\) is velocity) of all molecules at the same temperature are equal, irrespective of their mass. Speeds of large molecules with large mass are rather high as well. So, a macromolecule with a molecular mass of 10,000, that is, several hundred times larger than the mass of air or water molecules, still moves at a speed of almost 100 km/h.

Collision rates given in billions (5–6) per second are difficult, if not impossible, to comprehend. An analogy that may be somewhat less difficult to process is to imagine that one person bounces two times into every citizen of China and India (combined) in 1 s. The other analogy is that someone is standing in a tightly packed group of 200 people and is pushed 20–30 million times by each of those 200 people in 1 s.

The immense number of interacting molecules is usually associated with Avogadro’s number \(6.022 \times 10^{23}\) \((602,200,000,000,000,000,000,000,000)\). There are many papers with analogies that try to familiarize students with this number (primarily when studying chemistry). The analogies are so numerous that they can be sorted into six groups. However, only analogies using small or tiny objects and the volume occupied by these objects are considered vivid to some degree. Most of the other analogies compare the number with something almost equally inconceivable, such as the number itself using numbers in the millions, billions, and trillions–too large to have real meaning for most people (8).

Besides the attempt to visualize the vastness of Avogadro’s number, the mentioned analogies also serve to illustrate the difficulty of conceiving the minuscule size of simple molecules. For students studying diffusion during a physiology course, Avogadro’s number is not the principal target of the analogy. The target could, more profitably, be some other number, possibly more prone to effective analogies and equally helpful in illustrating the enormous number of molecules in a minute volume.

Physiology students are used to dealing with small objects. Cells, for example, are the focus of their interest on many occasions. As a result, a single cell and the number of molecules within a cell are candidates for an instructive analogy. The volume of an erythrocyte is \(\sim 90\ \mu m^3\). It is routinely calculated and presented as a part of blood count results (usually denoted as mean cell volume). If water molecules occupied the whole volume of an erythrocyte, we would end up with \(3 \times 10^{12}\) \((3,000,000,000,000)\) water molecules. This number, although not nearly as large and difficult to comprehend as Avogadro’s number, represents something usually not encountered. Two analogies can be presented to students to give them a better idea of the number of interacting molecules at the cellular level in processes that they are already studying.

The number of water molecules in a volume as small as one erythrocyte is between one-half and three-quarters of the number of erythrocytes in 1 liter of blood \((4–6 \times 10^{12}\) erythrocytes/l), and this last value is difficult to miss when reviewing blood count results.

The other analogy illustrates just how big the number of molecules within a cell actually is and, at the same time, gives students an idea of how small molecules really are. Chamomile pollen particles are approximately spherical in shape, and their diameter is 25 \(\mu m\). Being below the resolution of the eye, individual pollen particles can’t be seen, but the common perception is that pollen powder consists of tiny particles. The use of a simple magnifying glass would make them visible and prove the perception. If packed as tightly as possible, they occupy 74% of the available volume. It can easily be calculated...
that $3 \times 10^{12}$ of those particles, the same number as the number of water molecules in an erythrocyte, would fill a container of 33 liters.

The great velocity of molecules is the property that explains the rapidity of diffusion. The two factors that limit the rapidity of transport at longer distances are 1) the great number of collisions and 2) immense number of molecules, even along a path one cell’s diameter in width. The exact distance that differentiates short and long distances, when considering diffusion in the context of a physiology course, is actually the size of the cell (several micrometers). This size tells us up to what distance diffusion is rapid enough to perpetuate the processes that are considered to be characteristic of living beings.

Presenting the principal parameters and familiarizing students with them through the use of analogies before lectures on the movement of molecules across cell membranes help students see why diffusion is very rapid at short distances and why it is the principle transport mechanism within the cell. It also helps them to understand why, at longer distances, diffusion becomes extremely slow and inefficient and is substituted by the principal long-distance transport mechanism: circulation.

**GRANTS**

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**REFERENCES**