OSMOSIS: A MICROCOMPUTER LABORATORY TEACHER

ENRIQUE SOTO, TERESA CASTANEDA and MANUEL MARTIN

Centro de Ciencias Fisiológicas, ICUAP and Escuela de Computación, Facultad de Ciencias Físico Matemáticas, Universidad Autónoma de Puebla, Apartado Postal 406, Puebla, Pue. 72000 (Mexico)

(Received July 24th, 1992)
(Accepted September 17th, 1992)

A computer simulation of osmotic processes has been developed. Several experimental setups are graphically simulated and may be freely selected by the user. The simulation analyzes the basic factors which determine the osmotic pressure and volume flow of a solution (e.g. concentration, temperature, activity coefficient, Staverman's coefficient and external pressure). The program was written in Turbo Pascal™ to operate in IBM-PCs or compatibles. High quality graphical display of results maintains the students' interest. A user's guide and continuous help for the available options simplify its use. Computer simulation seems to be a very well suited aid for teaching osmotic phenomena, improving both theoretical knowledge and the ability of the students to empirically demonstrate some of the basic laws of osmotic phenomena.

Key words: Teaching; Education; Simulation; Computer; Osmosis; Ultrafiltration

Introduction

Osmosis is the tendency of two solutions of different concentration to mix by the flow of solvent from the more diluted to the more concentrated solution [1]. It is an expression of the more general tendency of energy to flow from a state of high potential to one of low [2,3]. Osmotic flow constitutes one of the most basic mechanisms which regulate the movement of substances across cellular membranes. Since cellular membranes are characteristically semipermeable, osmotic phenomena occur in practically all cells. Osmotic flow determines some cellular adaptative mechanisms in a changing environment. At the tissue and organs level, osmotic processes play a critical role in the regulation of movement of substances between the blood and the interstitial and intracellular fluids [4]. In plants, osmotic forces determine the displacement of water against the gravitational force [5,6]. Learning the basic principles of osmosis, allows the student to interpret and understand other more complicated processes, such as: movement of substances across cellular membranes, regulation of cell volume, absorption and excretion of substances, etc. [1]. The laws of osmosis are essential elements of theories which attempt to explain the mechanisms of fluid homeostasis in practically all living organisms. Thus, for students in
In general physiology courses, osmosis is very often explained superficially and only the van't Hoff equation is dealt with. Also, the experiments usually performed in the laboratory to study osmotic phenomena are very rudimentary. Students commonly misunderstand the dynamics of osmotic phenomena conceiving them as static and linearly related to the concentration of solutes in a solution. The software here presented intends to serve as an aid for teaching. It is designed as a laboratory simulation system, going from the most elementary experiments e.g. the measurement of the osmotic pressure of an ideal solution, to the most complex, such as the determination of the osmotic pressure difference between two non-ideal ionic solutions. The program also allows the user to study the interaction between osmotic and hydraulic forces by simulating a device with a piston upon which mechanical pressure may be exerted. In all experiments critical parameters may be varied at will.

**Software Description**

**Program basis**

The program is based in the solution of the van't Hoff, the Debye Mickel and the Kedem Katchalsky equations. The osmotic pressure ($\pi$) of an ideal solution was determined using the van't Hoff equation as follows:

$$\pi = \frac{nRT}{V}$$

where $R$ and $T$ have their usual thermodynamic significance, $n$ refers to the number of mols in the solution and $V$ to the volume of the solution [4]. van't Hoff derivation assumes that the solute is impermeant.

For more advanced calculations the van't Hoff equation was modified employing the activity coefficient instead of the concentration ($nIV$). To calculate the activity coefficient ($\alpha$) of a solution, we used the theoretical model of Debye Mickel [2,7,8]. This model proposes that the dissociation of ions in a solution, depends on the absolute value of the ionic valence, the ionic radii and the ionic strength of the solution [2,8]:

$$\log \alpha = \frac{K}{(e \times T)^{3/2}} |Z^+ \times Z^-| \times \sqrt{I}$$

where the constant $K$ depends on the ionic radii, $Z^+$ and $Z^-$ are the valences of the ionic pairs, $I$ is the ionic strength of the solution and $a$ is the dielectric constant of the solvent. The ionic strength is a measure of the intensity of the electrical field in the solution and is defined as half the sum of the concentration of each ion times the square of its valence:

$$I = \frac{1}{2} \sum C \times Z^2$$

where $C$ is the concentration.
The Debye Mickel equation correctly predicts the activity of solutions in which the concentration is less than 0.1 M. For more concentrated solutions, the activity coefficient deviates from the values predicted from the Debye Mickel equation. Thus, for these solutions we introduced a correction factor, based on a table of experimental values measured from solutions of different concentrations of representative ionic pairs [7]. To obtain the correction factor, the program identifies whether the ionic pair is uni-univalent (KCl type) or bi-bivalent (CaCl2 type). Then, the activity coefficient of the solution at 0.1 M is calculated using the Debye Hückel equation. The difference between the calculated value and that found in the table at the same concentration, is added to the activity coefficient value appearing in the table and which corresponds to the concentration selected by the user (if selected value does not exist in the table an interpolated value is used). Thus a whole family of curves, corrected for the ionic strength of the solution, is obtained based on the empirical values of the activity coefficients for KCl or CaCl2 solutions.

In order to calculate the osmotic flow, the program generates an arbitrary set of time units and solves the equation of Kedem Katchalsky for the osmotic flow across a semipermeable membrane [3,4,8]. These authors established that the volume flow across a semipermeable membrane is determined by osmotic and hydraulic components. The hydraulic flow is due to a pressure difference, and thence obeys Poiseuille's law; its rate being proportional to the pressure difference and the fourth power of the radius of the pore [9]. The osmotic flow could be understood as a diffusional movement of the solvent and is proportional to the temperature and the concentration of the solution [10]. Hence, according to the treatment of Kedem and Katchalsky the equation defining the volume flow (Jv) is:

\[ J_v = -L_p \Delta P + L_p \sigma RT \Delta C \]

where \( L_p \) is the filtration coefficient of a semipermeable membrane (equivalent to the permeability constant for the solvent), \( \Delta P \) is the pressure difference, \( L_p \sigma \) is the hydraulic coefficient, \( \sigma \) is the Staverman's coefficient and \( \Delta C \) is the concentration difference [3,4,8]. The Staverman's coefficient applies to membranes which are permeable to the solvent. It is an empirical coefficient indicating the ratio of the actual to the theoretical osmotic pressure; its value will therefore vary from unity to zero, 0 is 1 for an impermeant solute, 0 for a solute as permeant as the solvent; intermediate values are those for solutes to which the membrane offers some restriction relative to the solvent [11]. Values of \( L_p \) and \( L_p \sigma \) are selected by the user from a table based on a series of empirical values of different cell membranes according to Dick [12].

To simulate the experiments with the osmotic pump, we followed the original description of Levenspiel and Nevers [13]. A pipe open at the top but capped at the bottom by an ideal semipermeable membrane was lowered into the ocean. Due to the hydrostatic pressure water flows into the pipe but, since there is an osmotic pressure difference between fresh and salt water (23 atm), water flows out of the pipe. When the pipe is lowered further, beyond 231 meters, the pressure difference will exceed 23 atm. At this point, water flow due to hydrostatic pressure will be greater than the osmotic flow in the opposite direction, and fresh water will thus flow.
into the pipe. Since salt water is about 3% more dense than fresh water, if the pipe were lowered
enough, water would finally rise above the surface producing a perpetual fountain of fresh water [13].
The program calculates the fountain's pressure (level above ocean surface) based on the depth of the
pipe and on the density of the ocean according to the following equation:

$$dz = 231 - ((p_s/p_f) - 1)Z_{pipe}$$

where $dz$ is the level of water with respect to the ocean surface, 231 m is the level
at which hydrostatic and osmotic pressure across the membrane of the pipe are
equal; $p_s$ and $p_f$ are the densities of salt and fresh water, respectively; and $Z_{pipe}$ is the
depth of the pipe into the ocean.

Program operation

The program has been developed in Turbo PascalTM; to operate in IBM PCs and compatibles
equipped with at least one floppy disk drive. It run under almost any standard graphics system; we
tested it with VGA, EGA, CGA and Hercules monitors without problems. Memory requirements are at
least 640 kb RAM. The program has been designed in an interactive form; most actions are available by
pressing a single key. Options are continuously shown on the screen. Input-output protection schemes
are included to the extent needed to avoid errors. Disk data storage and retrieval and printer routines
have also been implemented.

From the main Menu the user may choose several options: review a brief text tutorial concerning the
relevant topics, calculate the osmotic pressure of an ideal solution, simulate an experimental
osmometric measurement of osmotic pressure, study the osmotic pressure difference between two
non-ideal ionic solutions, perform an ultrafiltration experiment and simulate the function of the osmotic
pump in the ocean.

To simulate the osmometer measurements, the user specifies the concentrations of the solutions, its
dissociation coefficient and the temperature. The program graphically displays an osmometer (Fig. 1)
and the final osmotic pressure. In all simulations pressure may be displayed in atmospheres, cm of
water, cm of mercury or Osmols.

For the experiments designed to analyze the osmotic pressure difference between two non-ideal
solutions, a database which stores information of some substances (molecular weight, valence,
dissociation and solubility) was implemented. The user selects the substances that compose the desired
solution and specifies them in grams or moles per liter. Warning prompts are shown if the solution
becomes saturated. Once the composition of each solution has been specified, its ionic strength and ac-
tivity coefficients are calculated. With these data, the resultant osmotic pressure is obtained and
graphically displayed in an experimental device with two solutions separated by a porous
semipermeable membrane (Fig. 2). Staverman's coefficient may also be varied, thus modifying the final
osmotic pressure.

For the ultrafiltration experiments, the composition of the solutions is also specified from the
database. The filtration coefficient of the membrane may be selected from a set of available options
including cellular membranes from frog eggs,
Fig. 1. Graphical display of the osmometer experimental setup. Water rises in the osmometer tube as a function of the osmotic pressure gradient between the internal and external solutions; this value is shown at the right (atm, cm of water, cm of mercury and Osmols). The inset plots hydrostatic pressure against time (in arbitrary units).

Fig. 2. Experimental setup for the measurement of osmotic pressure differences between two non ideal solutions. The osmotic pressure of solutions in compartments 1 and 2 and its difference are numerically displayed. Staverman’s coefficient (C.S) and units in which the results are expressed may be varied. Also a zoom may be selected; this last option shows solute molecules colliding against the membrane. Whereas some of the solvent molecules cross it.
dog erythrocytes, squid axon membrane, etc. [112]. The program generates a set of arbitrary time units, calculating the relation between the osmotic and the hydraulic fluxes. Data are graphically and numerically displayed, simulating a device equipped with a piston which allows the user to exert mechanical pressure upon it (Fig. 3). Graphics of the evolution of the osmotic and hydraulic flows, the osmotic and external pressures, and the volume of water in each compartment may also be displayed (Fig. 4).

Osmotic pump experiments prompt for the density of the ocean, default value 1.050 kg/l and the experimental setup is shown (Fig. 5). Pressing the arrow keys displaces the pipe upwards or downwards to different depths. The water level inside the pipe is graphically and numerically displayed along with the depth of the pipe. If the pipe is lowered far enough, the fountain begins to rise above the ocean surface level, as shown in Fig. 5.

Conclusions

This is a scientific teaching software, in which we have combined a series of simulated experimental setups, designed to highlight the basic laws of osmotic processes. Computer simulation has the advantage, over experimental procedures, that it permits changes in variables which would be difficult to control experimentally. Thus students can test some conditions which are obviously out of the scope of a
Fig. 4. Graph showing the temporal evolution of the osmotic pressure in an ultrafiltration experiment. Initially, osmotic pressure tends to decline as solvent flows between compartments. As the experiment proceeds, pressure was exerted upon the mechanical device reversing the flow of solvent. Thence, increasing the osmotic and hydraulic pressure differences between compartments.

Fig. 5. Setup of the osmotic pump experiments. Ocean waves and fish displacement allows the user to feel the beauty of ocean research. The pipe is moved upwards or downwards by using the arrow keys. At the left, the depth of the pipe is numerically and analogically displayed. The water level in the pipe with respect to the ocean surface is numerically displayed.
teaching laboratory. Furthermore, the slow time course of some osmotic phenomena, laboratory experiments often draws forth a passive view, leading the students to conceive osmotic pressure as a static final consequence of volume displacement and not as a dynamic force determining solvent flows. It is very common to find that students in the biomedical sciences conceive osmotic pressure, as a linear relationship between concentration, permeability and temperature. The implementation of ultrafiltration experiments and of the osmotic pump, intends to highlight also, some of the more simple interactions of osmotic and hydraulic forces. Undoubtedly the implementation of more complex force interactions (e.g., osmotic and electrochemical) would be highly desirable.

The program has been designed for students at the graduate and undergraduate level. It is self explanatory and no teacher or previous computer literacy are required. A text tutorial, helps to understand the theoretical basis of each of the processes simulated. Menu options are continuously displayed, facilitating the use of the program. The substances database is limited to some of the most common electrolytes found in biology. However, it allows to change or introduce new data concerning substances of particular interest to the user. The whole program and accompanying text have been written both in Spanish and English versions. All the data inputs are range protected and warnings about extreme values are displayed. In those cases in which the user incorrectly plans an experiment, catastrophic results may occur as in the osmometer experiments if the outside solution is of higher concentration than the inside solution. In every case results may be printed. A user's guide has also been designed to facilitate the program installation and use.

As we have previously proposed [14,15], one of the main advantages of using computer simulations in teaching, is that students also acquire some knowledge about the algorithms and computer constructs performed to simulate a physiological phenomena. Hence, students should be encouraged to understand the way in which the process has been simulated and the minimal elements which were considered as essential to model it.

Availability

A diskette with the program and a user's guide is freely available from the authors, by sending a blank diskette and $US10.00 for postage handling.

Acknowledgements

We wish to express our gratitude to Dr. Oscar Diez Martinez for critical reading of the manuscript. Partially supported by Secretaría de Educación Publica (SEP) grant DGICSA C90-O1-0472.

References

Osmosis, a microcomputer simulation

5 Dainty J: The polar permeability of plant cell membranes to water. Protoplasma, 57 (1963) 220-228.