A SIMPLE MODEL FOR TEACHING
FUNCTIONS OF THE KIDNEY NEPHRON

Dr. Harold L. Wilkinson
Department of Biology, Millikin University
Decatur, IL 62522

HISTORICAL BACKGROUND

Understanding the function of the kidney has been the undertaking of many brilliant minds. Its history dates back into the 1800's, when scientists such as Bernard, Bowman, and Heidenhain pioneered early thought about regulation of the fluid that bathed animal cells.

Claude Bernard (1878) is attributed with recognizing that higher animals have two environments to deal with in life: (1) the milieu exterior and the (2) milieu interior. He observed that the milieu interior never varied, consequently it provided a constant environment for cells by acting as a buffer against the ever-changing milieu exterior. 1

Today, most of us are aware that the milieu interior described by Bernard is the extracellular fluid surrounding cells, with the adjacent environment being the interstitial fluid and a removed environment being the plasma of the blood. W. B. Cannon (1929) explained that “the unchanging nature of the milieu interior was due to physiological control systems excited to action by slight deviations of state. This control system is now known to be the Kidney. It is easily shown that under all conditions the kidneys excrete a urine of such composition as to offset any tendency toward deviation in the composition of the plasma. 2

How this was accomplished was an issue of hot debate in the middle 1800's. Establishment of the nephron as being the structural unit of the kidney was generally accepted, but the function of the nephron was disputed. Two lines of reasoning were developed, one by Bowman (1832) and the other by Heidenhain (1874), which were not in agreement.3

Bowman's group claimed that the nephron produced urine by first excreting water and salts through the glomerulus and then adding secreted waste products such as urea and uric acid along the nephron. The eventual urine was concentrated by passive movement of water out of the nephron due to osmotic pressure differences across the wall. Blood pressure was the primary force creating urine and experiments correlating blood pressure changes and amount of urine formed was supportive of their hypothesis. The overall process was considered to be a passive process using natural gradients and forces.1

Heidenhain, on the other hand, an adherent of the vitalist theories of the day, claimed that the glomerulus secreted water and salts and that these secretions were enriched with various additions of salts, waste products and foreign substances by the tubule. Their theory required discrimination on the part of the glomerulus and tubule cells and was considered to be an active process.1

It was not until 1917 when Cushney, in
his monograph *The Secretion of Urine*, suggested a "modern theory" of urine formation which precipitated research that led to the understanding that we have today. Cushing proposed that the initial step in urine formation occurred at the glomerulus by filtration. The ultrafiltrate thus formed would have the same composition as plasma and was produced as a result of the hydrostatic pressure of the blood. Substances such as glucose, amino acids, etc., which are present in blood but not in urine, were thus thought to be reabsorbed by the tubule. Finally, it was proposed that large amounts of water would have to be reabsorbed in the tubule in order to account for concentrations of waste products such as urea. Secretion as a tubular process was denied.4

In the middle 1900's, through the exceptional work of Homer Smith and some of his students, our understanding of nephron function was clarified. From Smith's work concepts such as tubular secretion and clearance became known.

**BASIC CONCEPTS**

The purpose of this article is help the student of physiology understand the concepts elucidated by Homer Smith and his followers.

Although simple in principle, these concepts are often difficult for the beginning student to understand; therefore, it is helpful if the sense of vision, as well as other senses, can be used.

A first point for students to remember is that the kidney, more specifically the nephron, performs four basic functions: (1) filtration, (2) secretion, (3) reabsorption, and (4) excretion. The simple components of the kidney that perform these functions can be modeled as a filter attached to a tube, as in Figure 1.

- **Filtration** is defined as movement of water and solutes from glomerular capillary blood to lumen of Bowman's Capsule across the podocyte filter.
- **Secretion** is defined as movement of solutes from blood to tubular lumen across the cell layers of nephron tubule and peritubular capillary.
- **Reabsorption** is solute and water movement in reverse of secretion i.e. tubular lumen to capillary lumen.
- **Excretion** is the movement of solute and water along the nephron to its eventual destination in the pelvis and urinary bladder.

It is evident that the first three of these processes involve the movement of water or solutes between two compartments separated by one or more cell layers. This movement can be either passive, using concentration or electrical gradients, or active, using energy supplied by the cells.

**THE MODEL**

The components of the system modeled in Figure 1 (see page 4), although accurate in representing the actual nephron, lack the flexibility of being able to illustrate these movements across membranes and along the nephron within a classroom setting. Figure 2 (see page 4) represents a model that was developed to overcome these shortcomings and demonstrate the four basic processes of the nephron as well as passive movement of water and solutes between compartments. It is most
useful in conjunction with theoretical explanations of the basic principles involved. It is by no means intended to replace experiments that might demonstrate the actual function.

There are three parts to the model: a small square box with a 4 1/2 inch hole cut in the bottom that is covered with hardware cloth; a cylinder of hardware cloth that has been overlapped the entire length and half the circumference to create two different size holes on each half of the cylinder; and a rectangular box that is the same length as the cylinder with holes cut in the top and bottom to allow the cylinder to be inserted into it. The individual parts are illustrated in Figure 3.

The parts can be used separately or together to demonstrate the basic concepts mentioned earlier. They are used in conjunction with an artificial solution made up of beads or other particles to represent the body fluids (see Table 1). Most of the "solution" pieces are able to pass through the grid of the screen and because they come in variable sizes and colors they can be used to represent different molecules of blood and urine. Size differences give a degree of individual permeability to the pieces and can be used to advantage in a demonstration using the model. Previous use of the model has involved the types of particles listed in Table 1. It has been suggested that, instead of using air as the medium to represent water, small glass beads should be used because this would more closely simulate the actual situation. Figure 4 (see page 8) illustrates the relative size and appearance of the different solution particles.

**USING THE MODEL**

**PREPARATION OF A SOLUTION**

The concepts of volume and concentration can be reviewed with your students by using the particles to represent molecules of the solution. Prepare a solution of plasma by taking a 500 ml beaker and adding a measured amount of beads representing water. The water particles contained in a filled 100 ml beaker could be counted by the student and the idea that water has a concentration could be made. At this point have a few other students count out 100 pieces of

<table>
<thead>
<tr>
<th>Table 1: Items used to represent Plasma and Urine Solutes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type of Item</strong></td>
</tr>
<tr>
<td>------------------</td>
</tr>
<tr>
<td>Extrusions (Red or White)</td>
</tr>
<tr>
<td>Pop Beads (various colors)</td>
</tr>
<tr>
<td>Faceted Beads (8mm)</td>
</tr>
<tr>
<td>Starflakes (12mm)</td>
</tr>
<tr>
<td>Tri-beads (12mm)</td>
</tr>
<tr>
<td>Bubble Gum Balls</td>
</tr>
<tr>
<td>Poker Chips</td>
</tr>
<tr>
<td>Glass Beads</td>
</tr>
</tbody>
</table>
Figure 3

Glomerulus

Filter Screen

Tubule

Opening for Adding Solutes

One side of the screen has larger openings than the other to give variable permeability

Tubule made from 1/2" hardware cloth

Peritubule

Top view of Peritubule box shows partition that could be added to provide two longitudinal peritubular compartments

Opening for adding and removing peritubular solutes to one or two compartments
Representative Molecules

Glass Bead  Water
Extrusions  Small Protein or Carbohydrate
Pop Beads  Globulin or other Protein
Connected Pop Bead  Protein Dimer
Faceted Bead  Glucose or Inulin
Tri-Bead  Urea
Starflake  Amino Acids
Gum Ball  Large Proteins
Poker Chip

Figure 4
the particles representing solutes of the plasma. Have them place the particles in a graduated cylinder to see how much volume this represents. Have them express the concentration of the particles as 100 pieces per "x" ml. Add the particles to the 500 ml beaker containing "water". After thorough mixing of all the particles, fill a 100 ml beaker with a sample of your solution and then have some students determine the now diluted concentration of the different solutes. Point out that each solute has its own new concentration and that it represents the plasma concentration $P_x$. There are as many plasma concentrations ($P_x$) as there are solutes. This is also a good time to note that the combined concentration of all solutes represents the Osmolar concentration of the solution. Pedagogically, this is a good point to review the difference between Osmolar concentration and Molar concentration.

DEMONSTRATING FILTRATION AND GFR

Using only the part of the model representing the glomerulus, place your artificial solution into it in such a way as to avoid early passage of the particles through the screen representing the filtration membrane. Place the empty 500 ml beaker under the screen opening and while holding it securely in place, proceed to shake the arrangement in a random way so that a portion of the solution will pass through the screen without filtering out all of the smaller pieces, thereby leaving only large ones behind. Point out that the forces governing filtration are hydrostatic and osmotic pressures and that gravity, a dominant force here, would have no effect of the in vivo situation. The sample you have collected in the beaker represents the ultrafiltrate.

- Have students measure its volume and the concentration of the different solutes. Does the concentration match what is left in the glomerulus? In vivo it does. If it is not reasonably close you haven't shaken randomly enough.

- Are some particles not filtered? Red Blood Cells and large proteins are usually unable to pass the filter.

- Point out that the volume you have collected divided by the time of shaking represents the glomerular filtration rate. (GFR = mls filtrate/time of filtration)

- Also point out that each solute has its own filtration rate ($F_x$) which can be determined by dividing the number of pieces in the entire filtered sample by the time of shaking. ($F_x = \text{grams solute } \frac{x}{\text{time of filtration}}$).

At this point you could introduce the mathematical relationship that $F_x$ is also equal to $(GFR)(P_x)$. Have the class members calculate this value using values previously measured with this system and compare the theoretical with the actual.

DEMONSTRATING REABSORPTION AND EXCRETION

The property of reabsorption is demonstrated using the peritubular portion of the model. The wire representing the tubule should be in place in the peritubular box. While holding the box at a 45 degree angle and with the lower end of the model positioned over a shallow pan, add the
filtered material from the 500 ml beaker. (If the tubular screen has been prepared with two size openings, be sure that one of the two halves is on the lower side of the angled setup). As the artificial ultrafiltrate passes through the tubule its contents will be changed as particles pass out into the peritubular space by "reabsorption". Now have the students examine the solution (artificial urine) in the collecting pan. The volume of particles collected divided by the time of passage represents the urine flow rate (V). By counting the number of pieces of each solute and dividing it by the total volume the urine concentration of each solute (Ux) can be determined. Individual excretion rates (Ex) can be determined by multiplying (V)(Ux). The reabsorption rate can be determined by opening the small door on the peritubular box and emptying the contents into a beaker. By counting the number of pieces of each individual solute and dividing this by the time of passage you will get the individual reabsorption rates (Rx).

DEMONSTRATING CLEARANCE

Now we are ready to demonstrate the concept of clearance. Clearance (Cx) is defined as the volume (ml) of plasma that is cleansed of all of a particular solute per minute. Each substance in the plasma then has a clearance rate. All substances but water have positive clearance rates. Clearance, in order to demonstrate it accurately, must be performed on an intact kidney system but for our purposes the intact nephron model will do. Start by placing a sample of your artificial plasma into the glomerular box. Position the opening over the upper end of the peritubular box and then add a collecting beaker or box to the other end. While noting the elapsed time, proceed to shake the setup thoroughly until you have a sufficient quantity of artificial urine. Note that there are only two fluids that you can work with or measure, plasma and urine. The ultrafiltrate cannot normally be sampled clinically. To determine the clearance you must know the plasma concentration of each solute (Px), the urine flow rate (V), and the urine concentration of each solute (Ux). After determining these values they can then
be inserted into the formula:
\[ C_x = P_x \frac{V}{U_x} \]
and the clearance may be calculated. Take time at this point to explain the analogy with the actual kidney. Discuss shortcomings and weaknesses of the model in accurately representing the intact kidney.

**SUMMARY**

With careful preparation and forethought this model can be used to explain in a simplified way the workings of the kidney nephron. It can introduce the students to the mathematical relationships between the four functions of the kidney and help them to develop a working knowledge of the application of these relationships in clinical nephrology. Basic chemical processes such as filtration, concentration, diffusion, osmosis, etc. can be effectively demonstrated, allowing the students to actually visualize what happens.

**LITERATURE CITED**


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**Illinois Association of Community College Biologists**

**Spring 1990 Meeting**

On Saturday, April 21, 1990, the IACCB will meet in Chicago to spend the morning at the Shedd Aquarium for a "behind the scenes" tour. After lunch at the Field Museum, members will learn how to better use the Field Museum for educational purposes.