MODULE 3:

Principles of Dialysis

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Objectives

*After completing this module, the learner will be able to:*

1. Define the basic principles of diffusion, filtration, ultrafiltration, convection, and osmosis.
2. Explain how diffusion, filtration, ultrafiltration, convection, and osmosis relate to solute transport and fluid movement during dialysis.
3. Describe the principles of fluid dynamics and how they relate to dialysis.
Introduction

Hemodialysis may seem complex, but it is based on simple scientific principles. This module will help you understand these principles and how they are used in dialysis. Dialysis replaces three main kidney functions:
1. Removing wastes from the blood
2. Removing excess fluid from the blood
3. Keeping electrolytes (electrically charged particles) in balance

You will learn how these three functions are replaced by the dialyzer.

Scientific Principles Used in Dialysis

SOLUTIONS

A solution is a mixture of a solvent and a solute. The solvent is a fluid. The solute is any substance that can be dissolved into the solvent.\(^1\) So, in salt water, water is the solvent and salt is the solute.

Dialysate is the solution that is used during dialysis. Water is the solvent. The solutes are electrolytes (e.g., potassium, calcium, sodium, magnesium, and chloride ions) and glucose (sugar). Electrolyte levels in dialysate closely match the levels in human blood. This reduces the loss of these electrolytes out of the blood and into the dialysate during dialysis.

The patient’s blood electrolyte levels can be controlled by changing the dialysate. Adding an electrolyte to the dialysate at a level higher than in the blood will allow the electrolyte to enter the patient’s blood during a treatment.\(^2\)

SEMIPERMEABLE MEMBRANE

A semipermeable membrane is a type of thin, flexible filter—a barrier that allows only particles smaller than a certain size to pass through it. Think of the membrane as a strainer you might use to drain noodles. The water drains out, but the noodles are too big to pass through the holes. In dialysis, the semipermeable membrane’s holes allow small molecules, such as water and urea, to pass through easily. Middle molecules can also pass through, but more slowly. The small size of the pores keeps larger molecules and blood cells from passing through the membrane.\(^2\)

DIFFUSION

Diffusion is the process by which atoms, molecules, and/or other particles move from an area where they are in high concentration to an area where they are in low concentration.\(^1\) For example, when a tea bag is placed in hot water, molecules from the tea leaves diffuse into the water and flavor it (see Figure 1 on page 78). Diffusion can occur in solids, gases, or liquids, such as blood. Energy for the movement comes from the molecules themselves, and does not depend on outside forces.

In the body, substances move into and out of cells by diffusion through the cell membranes. In dialysis, diffusion occurs across an artificial semipermeable membrane. This is how wastes and fluid are removed from the patient’s blood, and electrolytes are balanced.

The following factors affect all diffusion—from tea bags to hemodialysis.\(^2\)
Factors Affecting Diffusion: the Nature of the Solution

1. Concentration gradients: How concentrated is the fluid on each side of the membrane? Solutes move through a semipermeable membrane from an area of greater concentration to an area of lesser concentration. Solutes can move through a membrane in either direction, but always toward the area of lesser concentration. A gradient is a difference. As the concentration gradient—the difference in solute concentration—increases, solute movement increases, too. Diffusion stops when the concentrations on both sides of the membrane are equal. Concentration gradients allow dialysate to remove wastes from a patient’s blood and to balance electrolytes in the blood with electrolytes in the dialysate.

2. Molecular weight of the solutes: How large are the dissolved particles? Smaller molecules diffuse more easily and quickly than larger ones. Large blood components, such as red blood cells, white blood cells, albumin, and platelets—as well as viruses and bacteria—diffuse more slowly because they are bigger. Small molecules, such as urea and salts, diffuse faster. Middle molecules may pass through, but more slowly.

3. Temperature: How warm is the fluid? Molecules move faster at higher temperatures, so warmer fluids allow faster diffusion. This is why you’ll get tea sooner if you put your tea bag in hot water instead of cold water. Dialysate temperature is controlled during dialysis for patient safety, comfort, and faster diffusion.

Factors Affecting Diffusion: the Nature of the Membrane

1. Membrane permeability: How plentiful and large are the pores? A membrane with more pores allows faster diffusion. Larger pores allow larger molecules to pass through. The membrane’s thickness and design also affect the diffusion rate (see Figure 2).

2. Surface area of the membrane: How big is the membrane? Surface area is the amount of membrane in direct contact with the blood and dialysate. Larger surface areas allow more diffusion.

3. Flow geometry: How do the fluids flow? In dialysis, blood flows one way while dialysate flows the opposite way (see Figure 3). This countercurrent flow of blood to dialysate speeds up diffusion, because with this
arrangement, a high concentration gradient between the blood and dialysate can be maintained throughout the length of the dialyzer. (A concurrent flow would occur if blood and dialysate moved in the same direction).

**OSMOSIS**

In diffusion, solutes move. In osmosis, the solvent moves across the membrane. Osmosis is movement of a solvent through a semipermeable membrane from an area of lower solute concentration toward an area of higher solute concentration. The difference in concentration is called an osmotic pressure gradient. In both diffusion and osmosis, movement goes on until the concentration of molecules equilibrates (becomes equal) on both sides of the membrane.

Imagine a jar divided in two by a membrane that allows water—but not glucose molecules—to pass through. If you fill one side of the jar with water, half of the water will slowly pass through the membrane, until the water level on both sides of the jar is the same. You could then dissolve sugar on one side of the jar, to create a difference in glucose concentration between the two sides. Osmotic pressure created by the sugar would draw water across the membrane to dilute the sugar water. In time, the level of sugar water would rise above the level of pure water. The more sugar you added, the higher the osmotic pressure would build, and the higher the sugar water level would rise.

Osmotic pressure can be overcome by hydraulic pressure using a pump, gravity, or other means. The total pressure on a fluid will include both...
osmotic and mechanical forces. In our jar, hydraulic (mechanical) pressure was applied by gravity. Water would be pulled into the sugar water until the osmotic pressure is equal to the pressure created by the weight of the water. The osmotic pressure drops as the sugar water is diluted.

Hydraulic pressure can reduce or overcome osmotic pressure. If you raised the hydraulic pressure on the sugar water in the jar, you could overcome the osmotic pressure. This would cause water to move from the sugar water back into the pure water. This principle is the basis for reverse osmosis water treatment devices.

**FILTRATION AND ULTRAFILTRATION**

Filtration is movement of fluid through a filter as the result of hydraulic pressure. Fluid will always move from a higher pressure to a lower pressure. The filter traps any matter that is too large to pass through it.

In dialysis, ultrafiltration (UF)—water removal from blood due to a pressure gradient across a membrane (see Figure 4)—is used to remove excess water that has built up. The filter used in UF is a semipermeable membrane.

Convection is the transfer of heat and solutes by physical circulation or movement of the parts of a liquid or gas. In dialysis, convective transport leads to solvent drag. As a solvent crosses a semipermeable membrane, it drags along smaller solutes.

**FLUID DYNAMICS**

A fluid is a liquid or gas that changes shape at a steady rate when acted upon by a force. The field of “dynamics” addresses the motion and equilibrium of systems. Fluid dynamics applies to dialysis, because it describes how two fluids—blood and dialysate—are pumped through tubing. Within the dialyzer, blood and dialysate are kept apart by the semipermeable membrane.
Several forces affect the movement, or flow, of fluid through tubing. Flow rate is the amount of fluid that flows through the tubing in a given period of time (e.g., 10 milliliters per minute, or mL/min). Flow velocity is the speed at which the fluid moves through a given length of tubing. Velocity is based on the rate of flow and the area of a cross section of the tube. So, if the flow rate is held constant but the cross section of the tube is reduced by half, the flow velocity will double.

Imagine that one gallon of water must move through a tube with a one-square-inch cross section in one minute. If you reduce the cross section of the tube by half, to 1/2 square inch, the fluid will have to go twice as fast to move a gallon of water in one minute; flow velocity would need to double. Adding a piece of tubing with a 1/2-square-inch cross section to the end of a tube with a one-square-inch cross section will have the same effect: doubling flow velocity. Because all the water must pass through the narrowest part of the tube, the narrowest part of any tubing limits the maximum flow velocity.

Adding a second, narrower, piece of tubing also increases resistance to the flow—another force that affects the movement of fluid in a tube. In any tubing, simple friction creates some resistance to the flow of fluid. But a restriction, such as a narrowing of the tube, will greatly increase resistance and so will increase the pressure of the fluid in the tube.

If, for example, the end of a soaker hose is open, water will flow through it freely (see Figure 5). Because there is little resistance, there will be little pressure and the water will dribble out of the holes slowly. But if you raise the pressure, increasing the resistance, the water will squirt out of the holes forcefully.

The pressure in any fluid system is always related to the flow and the resistance; the greater the flow and the greater the resistance, the greater the pressure.

Applying Scientific Principles to Dialysis

Dialysis patients’ kidneys don’t work. So, they come to dialysis with wastes in their blood, extra fluid between their cells and in their blood vessels, and often with electrolyte imbalances. The main tasks of dialysis are to remove wastes and excess fluid, and balance electrolytes.

Blood itself is a solution. Water is the solvent, and electrolytes, glucose, and many other substances are the solutes. Blood also has many particles, such as red and white blood cells. The principles of fluid dynamics, diffusion, UF, and osmosis apply to each dialysis treatment. To use the principles, we expose the patient’s blood (a solution)—to

![Figure 5: Positive pressure in a soaker hose](image-url)

The principle of positive pressure can be illustrated with an ordinary soaker hose. Positive pressure is exerted against the sides of the hose as the water moves through it. Excess water is forced through the holes.

The same principle is true in the semipermeable membranes used in dialysis. The amount of fluid forced or removed through the pores depends partly upon the amount of pressure pushing the fluid through the line.
the dialysate (another solution)—with a semipermeable membrane between them.

**FLUID COMPARTMENTS**
To understand how dialysis removes fluid, you must know how fluids work inside the body (see Figure 6). The human body is made mostly of fluids. Fluids are found inside the cells, tissues, and vasculature (blood vessels). Each of these three sites is a “compartment.”
- The *intracellular* compartment is fluid inside the cells.
- The *interstitial* compartment is fluid in between cells.
- The *intravascular* compartment is blood inside the blood vessels.

Differences in the level of sodium and electrolytes between compartments (gradients) cause water to move. The body tries to keep equilibrium—to have the same level of osmotically-active solutes in all three compartments. If the level is different, water will move from one compartment to another until they are equal. During dialysis, only fluid from the intravascular compartment—the bloodstream—can be removed.

**FLUID DYNAMICS IN DIALYSIS**
Fluid dynamics create changes in pressure as blood is pumped out of the patient’s body and through tubing and the dialyzer. Together, the tubing and dialyzer are called the extracorporeal (outside of the body) circuit.

When the dialysis machine is switched on and treatment starts, the blood pump speeds the flow of blood from the patient. Blood passes through the needle—the first restriction in the circuit. Because the blood pump is pulling—rather than pushing—blood through this restriction, the pressure created is usually negative: less than zero. The amount of flow and restriction determine negative pressure, just as with positive pressure (see Figure 7). As the flow or the restriction increases, the pressure will decrease. (The dialysis machine checks this pressure in the blood tubing before the blood pump [pre-pump arterial pressure].)

As the blood passes through the blood pump, it is pushed against the resistance of:
1. The tubing
2. The tiny hollow fibers in the dialyzer
3. The small opening of the (venous) blood-return needle (or catheter)

This resistance creates positive pressure inside the lines and dialyzer fibers. As blood passes through these resistances, the pressures change. The highest positive pressure is measured in the arterial header, where blood enters the dialyzer fibers (post-pump arterial pressure). As blood moves through the fibers, resistance drops, so pressure drops, too. The pressure measured after blood leaves the dialyzer (venous pressure) is the lowest positive pressure in the blood path. The average pressure of blood entering and leaving the dialyzer fibers is the true amount of force (positive hydraulic pressure) that aids UF of water out of the blood, through the membrane, and into the dialysate.3

Dialysate flows through the dialyzer and around the hollow fibers in one direction. Blood flows in the opposite direction for countercurrent flow. The machine can control the pressure differential between the blood and dialysate compartment as needed to reach the desired fluid removal. This pressure difference across the dialyzer membrane is called transmembrane pressure (TMP).2

**DIFFUSION IN DIALYSIS**

Let’s review how diffusion takes place inside the dialyzer (see Figure 8 on page 84). The hollow fibers in the dialyzer are the semipermeable membrane. Blood passes through the insides of these tiny fibers (capillaries); dialysate surrounds them on the outside. Molecules of a certain size range pass back and forth between the blood and dialysate, always moving from an area of higher concentration to an area of lower concentration.

Wastes in the patient’s blood diffuse across the membrane and into the dialysate. Used dialysate is sent to a drain and replaced with fresh dialysate, to maintain a high concentration gradient. This gradient allows as much waste as possible to be removed from the blood during each pass through the dialyzer.

Electrolyte balance is also maintained with diffusion. It is vital to patients’ health to keep the right level of electrolytes in the blood. To control the balance, electrolytes can be added to the dialysate.
Electrolytes will move until the concentration is equal on both sides of the membrane. Keeping a constant low level of an electrolyte in the dialysate ensures that the excess is removed without allowing the levels in the blood to drop too low.

Diffusion occurs continuously in the patient’s body. As cleansed blood is returned to the patient, it slowly dilutes the rest of the blood. The drop in the concentration of solutes in the blood creates a gradient between the blood plasma (liquid portion of blood) and the fluid in the cells and tissues. Because these cells have their own membranes, solutes—such as wastes and certain electrolytes—slowly pass out of the patient’s cells and into the bloodstream. From there, they are dialyzed. This process allows some of the wastes from other body compartments to be cleared from the body by dialysis. This slow process of diffusion is why dialysis treatments require more than one pass of blood through the dialyzer to clear wastes from the blood.

The nephrologist factors in diffusion when prescribing a treatment. He or she can choose a large or small dialyzer, based on the patient’s body size, the length of the treatment needed, and the size of molecules to be removed. The only thing that cannot be chosen is the size of the patient. To get an adequate treatment in a large patient, the doctor can increase treatment time and/or dialyzer size (clearance) to remove more wastes.2

**UF IN DIALYSIS**

UF requires pressure to force fluid through the membrane. The dialysis machine can create a hydraulic pressure difference, with higher pressure in the blood compartment than in the dialysate compartment. This TMP pushes excess water out of the blood and into the dialysate.

A dialysis prescription calls for taking off enough fluid to bring a patient to an estimated dry weight (EDW) by the end of the treatment. To figure out how much fluid you need to remove, just subtract a patient’s EDW from the predialysis weight. Then add the amount of any fluids the patient will receive during the treatment.

**CONVECTION IN DIALYSIS**

As water (a solvent) moves from the blood compartment to the dialysate compartment, molecules of dissolved solute are dragged along too (solvent drag). This process of solvent
movement is called convection. The ease with which the solute is dragged along by the solvent is determined by the size of the solute molecule compared to the size of the membrane pores. Smaller solutes move easily, so the solution can sieve across the membrane without any change in concentration. But larger solutes move more slowly and the rate of convective transport is also slower. Thus, the convective transport of a solute depends on how porous (both size and numbers of holes) the membrane is. This measurement of porosity is known as the sieving coefficient (SC) of the membrane. An SC of 1.0 means that, barring other clinical factors, the membrane could allow 100% of a given solute to pass. An SC of 0.4 means that only 40% of a solute would pass and 60% would be kept in the blood.

**OSMOSIS IN DIALYSIS**

Osmosis also plays a key role in dialysis. The pressure of UF pushes fluid out of the blood and into the dialysate. But osmotic forces decide which way water will move from one body compartment to another. In hemodialysis, diffusion lowers the solute concentration in the blood. Higher solute concentration in the tissues and cells then pulls water out of the blood. Rapid drops in blood volume can occur, which causes drops in blood pressure and other symptoms. Often, sodium is added to the dialysate, so it diffuses into the blood. The higher blood sodium draws water from other body compartments into the blood, so it can be removed by UF. The sodium in the dialysate is then lowered towards the end of the dialysis treatment to pull the sodium back out of the bloodstream.

**Conclusion**

Understanding the principles of dialysis is key to knowing how a patient's blood is cleaned by dialysis. Diffusion, filtration, UF, convection, and osmosis must occur in the right amounts at each treatment.

If you understand dialysis well, you will see how the treatment can be tailored to meet the needs of each patient. You can play a crucial role in delivering the best dialysis treatment each patient can receive.
Learning Activities

INSTRUCTOR TOOLS
- Potassium permanganate (available from the lab or pharmacy)
- Sheets of cellophane (to make bag)
- 3-cc syringe (without needle, to fill bag)
- Clear glass beaker, large jar, or a bowl
- Soft rubber or silastic tubing or hose that will fit on end of faucet
- Tea bag
- Sodium chloride (table salt)

ACTIVITIES
- Select a patient dialysis record and review the principles of dialysis as seen in the chart.
- Demonstrate the principles of flow, pressure, and resistance by attaching a 12-inch segment of soft rubber tubing to a faucet. Hold the rubber tubing perpendicular to the faucet and turn the water on until water flows slowly out the end of the hose. Do not adjust the flow, but lower the hose into the sink or a bucket. You will notice that the flow of water is faster, because resistance to the flow has been decreased. By increasing the flow, the pressure of the water coming out is also increased. Now, gently pinch the tubing closer together, increasing the resistance to the flow. You will notice an increase in the pressure as the water comes out the end of the tubing. Flow, pressure, and resistance are closely related, and each has an effect on the others. This is also true in the hemodialysis circuit. An obstruction at the venous needle increases resistance to the blood flow, increasing the venous pressure reading.
- Demonstrate diffusion and filtration by placing a tea bag in a glass of hot water. Tea coloring will slowly diffuse through the glass of water. Meanwhile, the semipermeable membrane of the tea bag has filtered the tea leaves, preventing them from passing across the membrane.
- Demonstrate filtration and UF by soaking a sponge in water. Hold the sponge over the bucket of water and watch the sponge filter the water. Now apply positive pressure to the sponge (squeeze it) and see how much more water can be removed, or ultrafiltered, by applying pressure.
- Demonstrate diffusion and osmosis by making a bag out of a piece of cellophane. (Be sure to wet the membrane so that it does not tear as easily.) Into this bag, place 1 cc of potassium permanganate solution and suspend the bag in a beaker or glass of water. Very quickly, the potassium permanganate will diffuse into the water. At the same time, osmosis will take place. The volume inside the bag will increase as water enters the bag to equalize the concentration on both sides of the membrane. This process can also be demonstrated with salt water in the bag instead of potassium permanganate. The water in the glass will become salty, while the volume in the bag will increase as water moves into the bag in an attempt to equilibrate the concentrations of salt on both sides of the bag.
- Diagram the extracorporeal blood circuit; label compartments, direction of flow of blood and dialysate, and points of resistance.
- Observe the calculation and application of TMP to dialysis.
- Note patient predialysis and postdialysis weight.
References


