Hemodialysis Machine

Introduction:

- Dialysis is the removal of substances by means of diffusion through a membrane. Dialysis is used to replace the normal function of the kidneys in a patient with kidney failure.
- The loss of kidney function can be either acute or chronic. In acute renal failure, which can be caused by accident or disease, the kidneys will eventually recover their normal function.
- In the absence of dialysis, the patient would die before the kidneys recovered. In chronic renal failure, the kidneys are permanently damaged and, in the absence of either a kidney transplant or regular dialysis, the patient will die.
- Two types of dialysis are used. In peritoneal dialysis, the dialyzing fluid is run into, and then out of, the patient's abdomen. This is a relatively simple technique that does not need either expensive equipment or access to the circulation, and it is used for certain patients with acute renal failure. Continuous ambulatory peritoneal dialysis (CAPD) has made peritoneal dialysis suitable for long-term use in chronic renal failure.
- In hemodialysis, blood is continuously removed from the patient, passed through an artificial kidney machine, and then returned to the patient.
- Chronic renal failure patients who have not had a kidney transplant and who are selected as suitable for dialysis will be treated either by hemodialysis or peritoneal dialysis. Alternatively, a kidney can be removed from a live donor (usually a close relative) or from a person who has just died and can be used to replace the kidneys in the chronic renal failure patient.

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- Obviously, the safety-critical aspects of the equipment design are extremely important. The patient will need two or three dialysis sessions every week, each of several hour's duration.

The function of the normal kidney

- The two kidneys are bean-shaped organs, about 12 cm long and 150 g in weight.
- They are situated on the back of the abdominal wall. The top of the kidneys lies beneath the bottom two or three ribs and each contains about a million nephrons (figure 1). The nephron has two parts, the glomerulus and the tubule. The function of the glomeruli is to filter the plasma which is circulating in the capillary loops within Bowman’s capsule. This is a passive process—it does not require any energy. The blood pressure in the capillary loops is about 60 mmHg, and about 25% of the cardiac output goes to the kidneys.

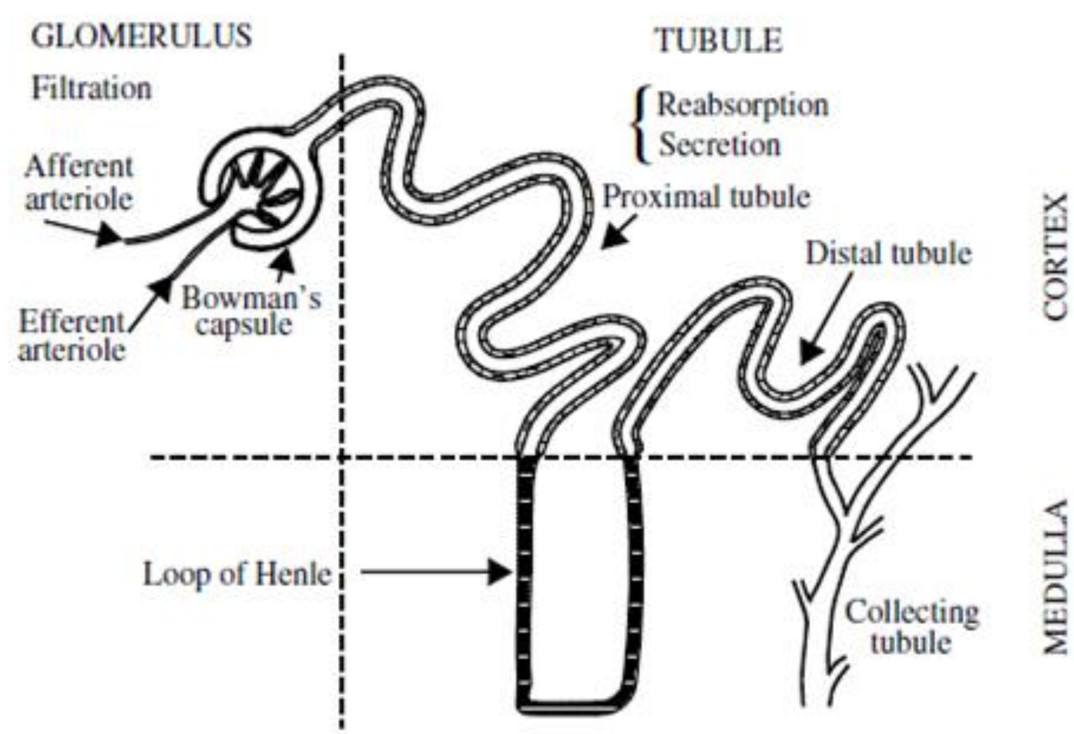


Figure 1. Diagram of a single nephron.

- The output of filtrate is about 1 ml/s/kidney, i.e. about 180 l day^{-1}. The total plasma volume is about 3 l, so that the plasma is filtered through the kidneys about 60 times a day. The filtrate then passes into the tubules. The total length of the tubules in each kidney is about 50 km. The tubules re-absorb electrolytes, glucose and most of the water, giving a total urine output about 1–2 l day^{-1}. This is an active process, which uses energy, and is continuously adjusted to maintain the correct fluid and electrolyte balance in the body.
- The composition of the blood is very complex. The most important electrolytes are sodium, potassium, chloride, bicarbonate and calcium.

- The processes of filtration and re-absorption, together with secretion from the distal tubules, maintain the correct level of the electrolytes.
- Any departure of the electrolyte levels from normal will have an immediate effect on the health of the patient. If the serum sodium level is elevated, the patient's blood pressure will increase. Potassium changes the excitability of the cells, and an increase of serum potassium can cause cardiac arrest without warning. An increased calcium level will cause the acid output of the stomach to increase, which can result in bleeding from peptic ulcers. A decrease in the calcium level will cause bone diseases. Most metabolic processes are very sensitive to the pH of the blood, which depends on the bicarbonate concentration.
- The electrolytes have low molecular weights (e.g. sodium 23, potassium 40). Organic chemicals in the blood have higher molecular weights (e.g. urea 60, bilirubin 600), and proteins have very high molecular weights (e.g. albumin 60 000, fibrinogen 400 000).
- Diffusion of substances across the dialysis membrane decreases with increasing molecular weight. Failure of the kidneys results in uremia (retention of urea in the blood) and the concentration of urea in the plasma rises steeply from the normal level of 5 mmol 1−1. All the body systems are affected, both by the increasing concentration of waste products in the blood, and by the electrolyte imbalance.
- <u>It can be seen that dialysis is much more than just the removal of waste products from the blood. Dialysis has to maintain the correct electrolyte balance within the body, maintain the correct pH of the blood, and control the fluid balance</u>.

Membranes

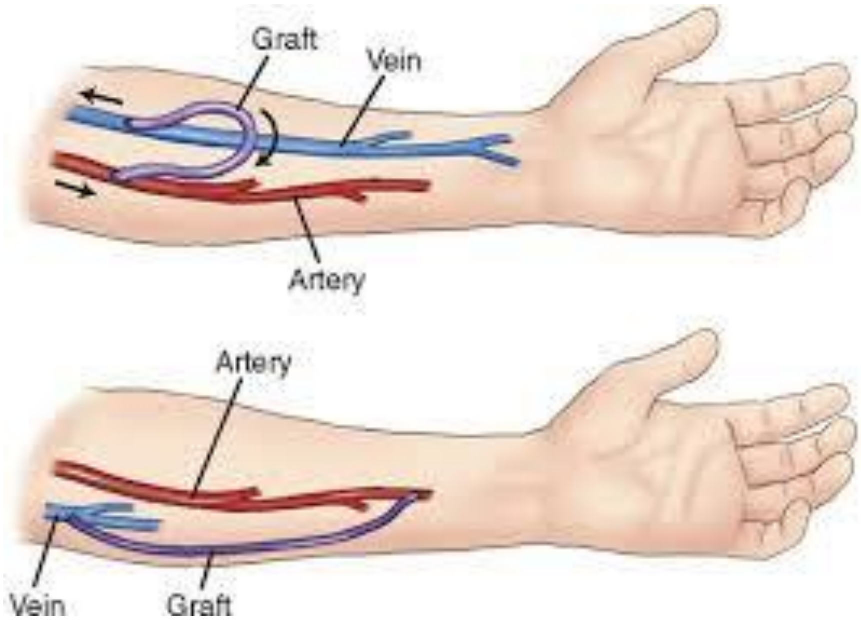
Membranes are made from a number of different materials including;

- Cellulose (processed cotton), Cuprophan.
- Substituted cellulose, where free OH^- groups on the surface of the cellulose are replaced with acetate groups.
- Synthetic material, e.g. polyacrylonitrate, polysulfone, polymethyl methacrylate.

Principles of hemodialysis

- Hemodialysis means "cleaning the blood" and that is exactly what this treatment does, blood is circulated through a machine which contains a dialyzer (also called an artificial kidney), the dialyzer has two spaces separated by a thin membrane, blood passes on one side of the membrane and dialysis fluid (dialysate) passes on the other.
- The wastes and excess water pass from the blood through the membrane into the dialysate, which is then discarded.
- It is a fairly lengthy process in which small amounts of blood are removed from the body, circulated through the hemodialysis machine, and returned to the body.

- To ensure that all the blood is cleaned properly, the hemodialysis treatment often lasts for up to four hours.
- People who are likely to require ongoing dialysis treatments usually choose to have a long-term access (a fistula) readied in their arm, fistulas are more permanent than catheters, and can last many years.
- A fistula is created in the arm by connecting a vein and artery under the skin, forcing the vein to become larger than normal.
- The dialysate used is different for each person, and is prescribed by the doctor to meet each person's own needs, the amount of time that must be spent connected to the hemodialysis machine is also different for each person.
- The dialysis machine is responsible for controlling the flow of blood, it also carefully monitors patient's status, making sure that blood pressure is in healthy ranges and that no air is in the tubing.



Diffusion

- The semi-permeable membranes used in artificial kidneys are typically about 10–20 μm thick (the more common thicknesses are 11, 13 and 15 μm), have a surface area of about 1 m^2 (varying between 0.5 and2.5 m^2), and have pores which are about 500 nm in diameter.
- Obviously, substances which are larger than the pore size will not be able to pass through the membrane. This class of substances includes protein molecules and most substances with a molecular weight greater than 40 000.
- Molecules with a molecular weight less than 5000 will pass easily through the membrane by diffusion, and molecules of intermediate weights (5000–40 000) will pass slowly. Dialysis will only remove a small quantity of amino acids (molecular weights 75–204) and of some drugs, because they are bound to the plasma protein, and will therefore not pass through the membrane by diffusion.

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Osmosis and ultrafiltration

- Water molecules will also diffuse through the membrane. The concentration of water molecules in the stronger solution is less than that in the weaker solution, so that water molecules will diffuse from the weaker solution to the stronger one.
- The net effect is, again, to make the concentration of the solutions on each side of the membrane the same. This movement of water from the weaker to the stronger solution is called osmosis (figure 2).
- If pressure is applied to the stronger solution, it is possible to stop the movement of water molecules across the membrane. The pressure needed to stop osmosis is the osmotic pressure. If the pressure is increased further, water molecules will be forced through the membrane. This could also be done by decreasing the pressure of solution B.
- The movement of water across a membrane as a result of hydrostatic pressure is called ultrafiltration. The amount of water which passes across the membrane is a function of the hydraulic permeability of the membrane, the transmembrane pressure and the surface area of the membrane.

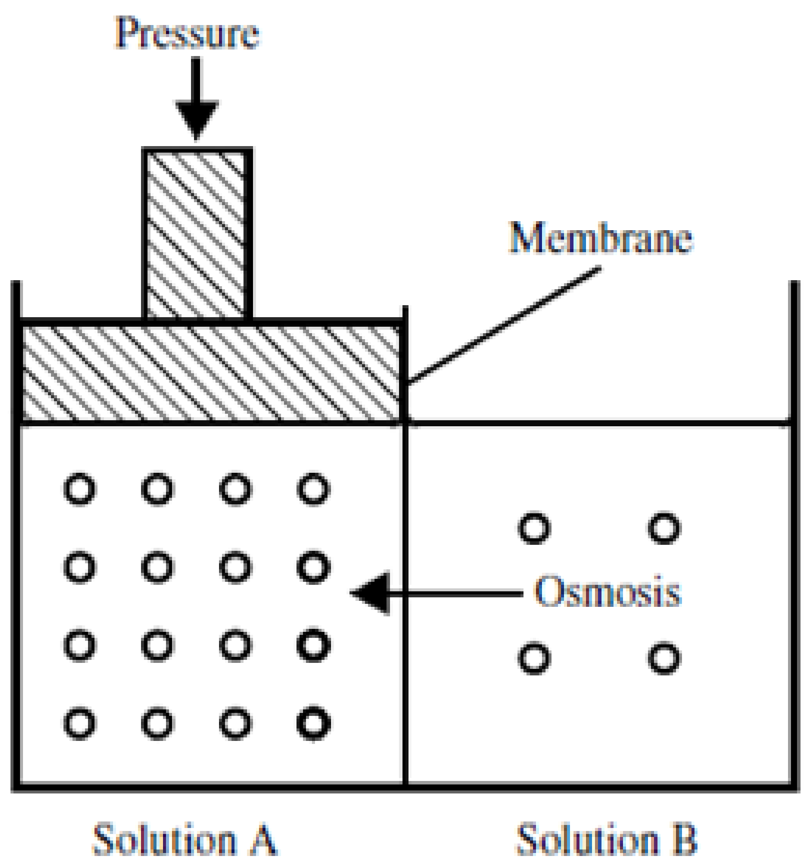

Figure 2. Osmosis. Water will diffuse through the semi-permeable membrane from the weak solution B to the strong solution A. If a hydrostatic pressure is applied to solution A, water molecules can be forced in the reverse direction.

The dialysis fluid

- The principles of making up a suitable dialysis fluid should now be clear. If the concentration of any dialyzable molecule is lower in the dialysis fluid than in the blood, it will be removed from the blood.

- The rate of removal will depend on the difference in concentration between the blood and the dialysis fluid. Some molecules should be removed as completely as possible, and are therefore left out of the dialysis fluid, so that the concentration gradient is maximized.
- Examples are urea, uric acid and creatinine. It is important that some molecules are maintained at the correct concentration in the plasma, and these are therefore added to the dialysis fluid at a suitable concentration. For instance, the plasma sodium level should be maintained at 132–142 mmol l^{-1}.
- Most patients with renal failure tend to retain body sodium, so it is usual to use a slightly lower concentration in the dialysis fluid to correct this. A typical concentration in dialysis fluid would be 130 mmol l^{-1}. The correct pH of the body is maintained by adding lactate or acetate to the dialysis fluid. The concentration of these is lower in the blood, so they diffuse into the blood, and are metabolized by the liver to produce the bicarbonate which regulates the pH.

- Calcium and magnesium levels in the plasma have to be controlled, and these produce particular problems. Both these ions are present in significant quantities in the water supply and vary both regionally, depending on the hardness of the local water, and seasonally. It is therefore usual to remove these ions from the water by using a water softener or a de-ionizer, so that the concentration in the dialysis fluid is always known.

- A further process that is used for purifying water is reverse osmosis. In principle, this involves placing the impure water, under high pressure, on one side of a semi-permeable membrane. The water which is collected on the other side of the membrane is very pure—typically 97% of the organic matter and 90% of the trace elements in the water supply will have been removed. The semi-permeable membranes are expensive to replace, so that the water supply is usually pre-treated. In particular, the membrane is destroyed by chlorine which is often added to water supplies. A large-scale reverse osmosis plant might consist of particle filters to remove suspended matter, an activated carbon column to remove chlorine, a water softener, and then the reverse osmosis unit. Final purification would be done by a de-ionizer followed by bacterial filters.

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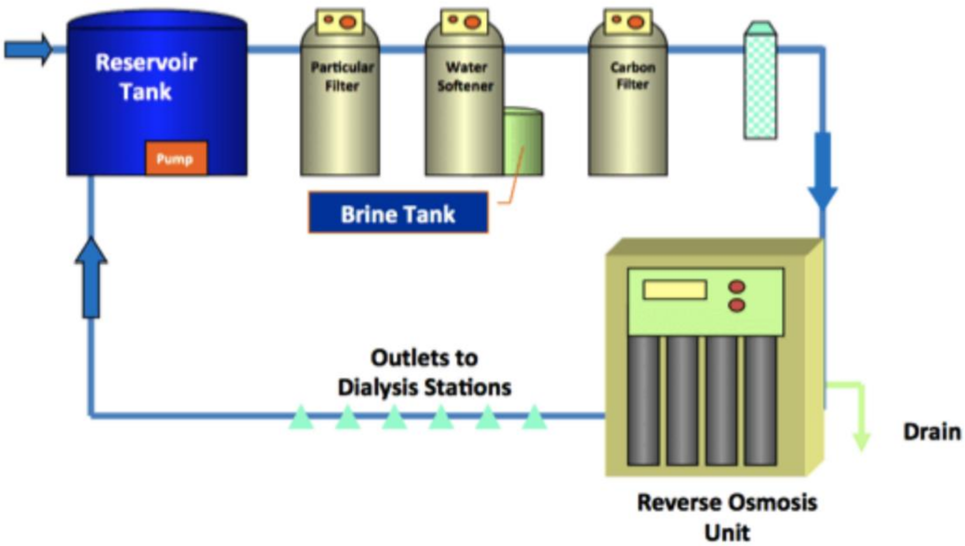

- **Ultrafiltration** is used to remove the excess water during hemodialysis. The dialysis fluid is made up to be isotonic (i.e., the total concentration of dissolved substances in the dialysis fluid is the same as in the blood), and the pressure gradient across the dialyser membrane is adjusted to give the required degree of ultrafiltration. This can be done either by increasing the pressure on the blood side of the membrane, or by decreasing the pressure on the dialysis fluid side.