Dialysis Machine: Effect of Technological Advancements

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Abstract

Eight decades ago, the first artificial blood purifier was invented. Today, in a world where spending twelve hours a week in treatment is not a viable option to many patients, the same bulky machines are still used. Fortunately, scientists have been vigilant, and the notion of developing a portable, reliable dialysis machine has been sought by many. In this paper, we first begin by analyzing the principle of Dialysis. Then we shed light on the technological innovations achieved ever since the first dialysis machine was mass-produced. The use of a high-flux membrane dialyzer, ultrapure dialysis fluid, and convection fluid has proved to greatly improve Dialysis. However, the difficulties still prevail. And so long as an efficient substitute can be found for the dialysate and proper healthcare can be given to patients at home, a portable dialysis machine is not going to be devised.

I. Introduction

The kidney is arguably one of the most important organs in the human body because it cleans the human blood from toxic wastes, so when it loses its renal functions, the person can be exposed to death. Hence, scientists have long hoped to invent a machine that simulates the function of the kidneys to clean human blood. The first successful machine for human Dialysis was invented and operated in the 1940s by a Dutch physician called William Kloff. Kloff came up with the idea of developing a blood purifier when he saw a patient with kidney failure. Kloff became interested in the possibility of artificial stimulation of kidney function to remove toxins from the blood of patients with uremia, or kidney failure. Although only one person was successfully treated, Cliff completed experiments to develop his design [1].

William kloff relied in his invention on the use of cellophane after discovering that (cellulose acetate) can be used as a semi-permeable membrane to purify the blood from waste.[2] The Clove machine consists of a horizontal rotating drum made of wood slices wrapped around 30-40 meters of cellophane (cellulose acetate) tubes, and the lower part of the device is suspended in a dialysate (salt solution).[2] The patient's blood enters the device through a cannula connected to the artery, and then the blood moves to the cellophane tubes wrapped around the rotating drum. When the drum rotates, the tubes sink into a solution, and the waste moves from the higher concentration to the lower concentration, meaning from the blood through the cellophane (semi-permeable membrane) to the solution [2]. The full dialysis cycle takes about 6 hours. And then the blood entire the body again through another cannula connected with a vein. This is how the first human blood cleaning machine was invented. After many developments in the field of Dialysis to this day, we have become dependent on two types of Dialysis: hemodialysis and peritoneal Dialysis.

Hemodialysis:

In hemodialysis, a doctor creates a vascular access site in the patient's arm before hemodialysis, then the blood is pumped from the body to the artificial kidney machine, which removes waste from the blood through a semi-permeable artificial membrane using the Dialysis solution and is returned to the body through tubes that connect it to the device. Needless to say, hemodialysis is done in hospitals [3].

Peritoneal Dialysis:

Peritoneal Dialysis, on the other hand, requires a catheter, or piece of tubing, placed in your belly. The dialysis solution enters the abdominal cavity [4]. The blood is purified while inside the body, where the protein membrane in the patient's abdominal cavity is used as a semi-permeable membrane [4]. Then the waste and the solution filled with the waste are collected. The filtering process is finished, the fluid leaves your body through the catheter. Since the blood does not need to leave the body, this process is carried out at home. As all this development came from studying the diffusion of gases, not liquids, and that is what will be discussed in this paper.

II. The scientific premise behind Dialysis

The principles of Dialysis can be tied back to Thomas Graham's discovery of diffusion. In his first article on Gaseous diffusion, Graham proposed that the gaseous flow was proportional to its density. He examined the escape of hydrogen via a tiny hole in platinum and observed that hydrogen molecules were moving out four times more quickly than oxygen molecules. His tests were designed in such a way that he could quantify the relative speeds of specific molecular movements. He also observed that heat enhanced the speed of these molecular movements while increasing the force that resisted the atmospheric pressure by a certain weight of the gas. Graham's numerical calculations revealed that the velocity of flow was inversely proportional to the square root of the densities. His law demonstrated that the specific gravity of gases could be assessed more precisely than usual. He also remarkably noted that diffusive gas escapes faster in a compound. This paved the way for the invention of the dialysis machine. In Dialysis, Blood flows by one side of a semi-permeable membrane, and a dialysate, or special dialysis fluid, flows by the opposite side. A semipermeable membrane is a thin layer of material that has holes of different sizes or pores. Smaller solutes and fluid pass through the membrane, but the membrane blocks the passage of larger substances. This replicates the filtering process that occurs in the kidneys when the blood enters the kidneys, and the larger substances are separated from the smaller ones in the glomerulus [5].

Another concept that is used in Dialysis is reverse osmosis (RO). Osmosis is the method through which water flows from a more concentrated solution into a less concentrated one across a semi-permeable membrane to reach a state of equilibrium. This means that clean water flows through the filter to the polluted water so that the concentrations are equaled: contrary to the goal of Dialysis. In reverse osmosis, an applied pressure is employed to counteract osmotic pressure and drive water from high contaminant concentrations to low contamination levels. It is therefore driven backward, and the contaminated water attempts to enter clean water, but since the filter must be passed first, the pollutants are held, and only the pure water goes through them, which is exactly what the goal of Dialysis is. Figure 1 illustrates the various mechanisms of flow discussed [6].

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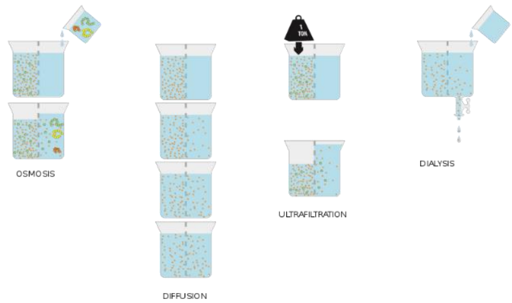

Figure 1: Osmosis, diffusion, ultrafiltration, and dialysis

general, there are pretreatment systems before dialysis devices, which deliver a high quality of water according to appropriate requirements, (primarily reverse osmosis [RO]). Scientists believe that the malfunctioning of pretreatment systems and the resultant poor feed water quality of the dialysis instrument might be related to some tragic occurrences at dialysis centers. Minimum trace element concentrations such as heavy metals in Dialysis can severely disrupt trace element concentration in individuals with Dialysis. Elements such as aluminum, nickel, cadmium, plum, and chromium must thus be taken

into account in particular. The rise in nickel level, for example, may lead to acute nickel poisoning. Aluminum also causes a disrupted balance of calcium phosphate not just in dialysis patients, but also in brain and bone conditions. over a long-term period of periods of time. Based on the above, reducing heavy metals in water is highly essential. [7]

III. Technological Innovations in Hemodialysis

I. Online Monitoring Technologies

Dialysis Automation and Profiling has made the process safer for the patient and the care team, reducing the un-physiologic incidences of human mistakes. Online Monitoring relies on the immediate information of Parameters blood volume (BV), dialysate, conductivity, urea kinetics, and thermal energy balance. The dialysis machine uses these measurements to apply automated actions to achieve the body's standards, such as sodium and potassium modeling and temperature control which affect the patient during or after the Dialysis.[8]

Effects of Automated sodium modeling

According to the received measurements, the machines decide to keep the current concentration or change it; one of these measurements is the dialysate sodium concentration. The machine tends to raise the dialysate sodium concentration to prevent intradialytic hypertension causing after dialysis vicious harms; Increased thirst, Intradialytic Weight Gain, and Hypertension; keeping in mind that fluid retention of ≥ 4 kg between two subsequent dialysis sessions is associated with a higher risk of cardiovascular death.[9]

No studies have proven that the high dialysate sodium concentration is better or more unsafe than the average dialysate sodium concentration. By the same token, some strategies keep the hemodynamic stability as safety rates away from the sodium modeling high risk, such as Temperature Modulation.[10]

But due to the online monitoring technology, the dialysis teams don`t require understanding the dialysis process, which makes the nurses use the high dialysate sodium concentration to reduce hypertension during the session, ignoring the long-term effects.

Effects of Automated potassium modeling

An analysis: part of the 4D study has been conducted which shows that a portion of high mortality is sudden death or abnormal cardiac rhythm, where:

- Patients without sinus rhythm were 89% more likely to die.
- Cardiovascular events and stroke risk increased by 75% and 164%, respectively compared with preserved sinus rhythm patients.
- Left ventricular hypertrophy with more than two-fold, increases the risk of stroke and sudden death incidences by 60%. [11]

The sudden shifts in the plasma potassium because of hemodialysis sessions can cause death in arrhythmia-prone patients. The lower concentration dialysate potassium is used to remove the excess potassium, being the necessary gradient.[12]

In the early stages of Dialysis, the plasma potassium concentration decreases rapidly, increasing the risk of ventricular arrhythmias even if the patient doesn`t have a prior record of heart disease.[12] The online monitoring has solved this problem by modeling the potassium concentration in dialysate in a way to minimize initial rapid deflation; also, every kind of patient has a different dialysate potassium concentration where intradialytic premature ventricular patients use fixed-rate (2.5 mmol / L) potassium or use a declining potassium concentration (3.9 to 2.5 mmol / L) and the one who has constant blood to dialysate potassium gradient of 1.5 mmol / L.[13]

A comparison was made between the two potassium dialysate concentration techniques with 30 arrhythmia-prone HD patients. Every patient went through the same acetate-free biofiltration sessions: randomly, the constant concentration (2.5 mmol / L) potassium and potassium the decreasing dialysate potassium. During the dialysis sessions, the Holter Electrocardiographic and plasma electrolyte measurements were recorded. After the sessions with approximately 14h, the results show that the constant potassium protocol is 3.9 times higher than the declining one in the premature ventricular contractions with no difference in any other points noticing that the experiment was conducted only on the potassium concentrations.[14]

Effects of Automated Temperature Modelling

Temperature modeling has been experienced by modifying dialysate temperature via blood temperature monitoring integration in the HD machines. The machine adjusts the dialysate temperature between 34 &35.5˚c according to the patient blood temperature of 37˚c. which results in cardiovascular stability during the HD treatment better than the normal dialysate temp.[15]

A review has conducted all the temperature adjustment techniques like reducing dialysate temperature, either an experimental, fixed Dialysate temperature reduction or a biofeedback temperature control. The review shows that reducing the dialysate temperature effectively decreases intradialytic hypertension without affecting dialysis adequacy, noticing that the long-term effects haven`t been examined yet.[16]

The mean positive impact of online monitoring technologies and techniques is the body factors stability during and after the dialysis process as in the potassium and temperature modelling techniques. On the other hand, sodium modeling has shown positive results in reducing hypertension during processing, with after processing harmful impacts like hypertension and increased thirst.

The most dangerous effect is the team knowledge of dialysis process basics & sudden incidences that can occur, whereas shown that automation of the process has canceled required understanding of dialysis process that the nurses and patients must-have.

IV. Purity of Dialysate and Dialysis Water

The water & concentrates used to produce dialysate and the dialysate are required to meet quality standards to reduce the injury risk of HD patients due to the chemical and microbiological contaminants that can be in the dialysate.[17]

Intact bacteria V.S. Bacterial Products

In the dialysate, there are non-vicious contaminants like intact bacteria that can`t proceed the dialyzer membrane, and vicious bacterial products such as endotoxins, fragments of endotoxin, peptidoglycans, and pieces of bacterial DNA which can cross into the bloodstream causing chronic inflammation due to stimulation on mononuclear cells. The induced inflammatory state may be an essential contributor to the long-term sickness associated with HD.[18]

Preparation of Ultra-Pure Water

Studies have shown that tiny fragments of bacterial DNA can maintain a chronic inflammation in HD patients by prolonging the survival of inflammatory mononuclear cells. [19]

With more attention in the dialysis centers to ultra pureeing, the water used in dialysate will help in reducing the chronic inflammatory cases. However, there aren`t studies demonstrating beneficial direct outcomes by using ultrapure water and dialysate, and if it is not helpful, it is not harmful. For ensuring safety, it`s recommended to ultra-pureeing dialysate water and the dialysate.

V. Hemofiltration & Hemodiafiltration

Hemodialysis is based on diffusion; exchanging solutes from one fluid to another through a semipermeable membrane along a concentration gradient. Even HD High-Flux Membranes don`t make a difference in the number of removed solutes because solute diffusivity decreases rapidly with increasing molecular size. Despite that, convection therapies such as Hemofiltration (HF) and Hemodiafiltration (HDF) can remove larger solutes.

Convection requires large volumes of substitution fluid which is covered with online ultrafiltration of dialysate and sophisticated volume control systems to maintain fluid balance.

Hemodiafiltration

HDF using a high-flux membrane dialyzer, ultrapure dialysis fluid, and convection fluid is highly efficient. As studies results, the high-efficiency

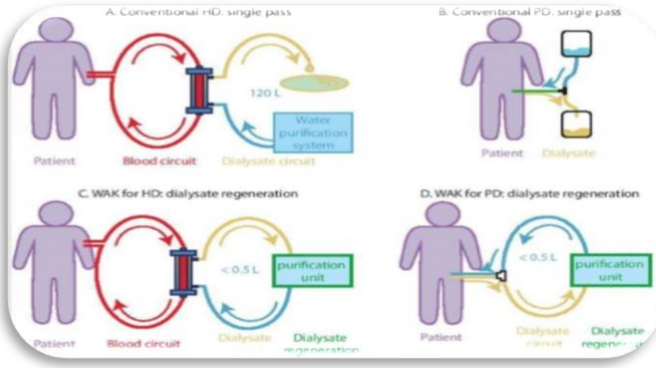

Figure 2: shown the massive improvement that occurred when trying to reduce the amount of (dialysate) solution used in the dialysis machine

online HDF is associated with a 35% reduced risk for mortality. Also, Regular use of online HDF is associated with reduced morbidity as compared with standard HD.[20]

Hemofiltration

A comparative study has been made on High-flux HF with ultrapure Low-Flux HD, shows a significant survival rate in HF compared with standard HF (78% V.S. 57% 3yrs follow-up). The study has demonstrated inclusion and logistic problems associated with online monitored Hemofiltration.[21]

The HDF and HF have ensured the efficient long-term effects by studies and patients reviews. However, it is needed to conduct more studies on these techniques to ensure the patient's safety.

VI. Difficulties facing the development of portable dialysis machines

Many obstacles have hindered the development of a smaller dialysis machine let alone a full-fledged wearable artificial kidney. The primary impediment has been the lack of an effective strategy to enable toxin removal without using substantial volumes of dialysate — a limitation that applies to both hemodialysis and peritoneal Dialysis.

In figure (2), we can see the massive improvement that occurred when trying to reduce the amount of (dialysate) solution used in the dialysis machine. As in (A), the patient’s blood enters the dialyzer and enters the dialysate solution from the other direction, then the blood is purified by using a semi-permeable membrane and the reverse osmosis process and after each cycle, the blood returns to the body and the solution is regenerated within the device in order to start a new cycle and the old solution is discarded and Each cycle requires about 120 liters of dialysate solution.[22] (B) represents peritoneal Dialysis (PD). During PD, the hypertonic dialysate is instilled into the peritoneal cavity via a catheter to allow diffuse and convective removal of waste solutes and osmotic removal of excess water across the peritoneum. [22]

After a certain period of time, the fluid (containing waste and excess water) is drained and disposed of. C and D is a representation of an artificial kidney that can be worn and transported, as it has a purification unit for the dialysate solution (dialysate regeneration), thus using a smaller amount of solution (<0.5L), and smaller device size.[22]

i. The use of sorbent material.

NASA has extensively studied ways to remove organic waste from solutions to restore potable water during manned space travel. These efforts have led to the development of sorbents (materials that absorb other compounds very efficiently), which can also be used to detoxify dialysate solutions. Almost all attempts to develop a wearable artificial kidney to date have incorporated absorbent materials into the dialysate circuit to replenish the dialysate. Sorbents containing activated charcoal are very effective in absorbing heavy metals, oxidants, and some uremic toxins such as uric acid and creatinine However, sorbents have historically proven ineffective in binding and removing urea, which has limited the usefulness of sorbent-based systems.[23]

ii. decomposition of urea by using enzymes

There have been many attempts by scientists to convert the urea compound contained within the dialysate solution to be reused into a compound of ammonia and carbon dioxide using enzymes, then the ammonia is absorbed using a sorbent called zirconium phosphate and the carbon dioxide is disposed of in the atmosphere. However, the combined use of sorbents and the enzymatic decomposition of urea are being tested by scientists and are under study.[23]

iii. Electro-oxidation

This method also dates back to early NASA investigations of using electrooxidation to electrolyze urea into carbon dioxide and nitrogen gas on metal-containing electrodes. After that, these gases are excreted into the atmosphere. But since urea is an acid, this can lead to the corrosion of the metal, so work must be done to develop this method.

Even if dialysis machines were to be reduced in size, there are many problems that patients with kidney failure will face. For example, health care, where patients in the hospital are safe next to the doctors and nurses, but if the Dialysis becomes mobile far from the hospital, there will be no strong health care, and a patient on portable Dialysis will not have access to a caregiver in the event of machine failure or exsanguination due to vascular disconnection.[23]

As we saw there are some of the ways that are being worked on to establish a purification unit for the dialysate solution in order to use a smaller amount of solution and thus reduce the size of the dialysis machine.

VII. Conclusion

It cannot be denied that impressive technological innovations in the field of Dialysis have been introduced in the past few decades from the first machine has been invented until now. However, the translation of these technical achievements into hard clinical outcomes is more difficult to demonstrate but some innovations really had helped dialysis be better. Despite that, it is unlikely that any of the innovations will be used in the next few years as there aren`t enough studies that ensure the long-term safety of patients. Furthermore, the need for a caregiver at disposal will remain a must if an artificial kidney were to be introduced.

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