International Journal of Applied Engineering Research ISSN 0973-4562 Volume 13, Number 7 (2018) pp. 5400-5403

A Low-Cost Portable Device for Combined Hemodialysis and Ultrafiltration

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Abstract

Uremia, the ultimate result of the chronic renal failure, is generally treated with artificial kidney based on the theory of hemopurification. Although the commercial artificial kidneys are available, they are usually space-occupying, expensive and demanding special-large-water-treatment-system, besides, the commonly used traditional intermittent hemodialysis mode also has apparent limitations. Considering the disadvantages of the commercially available artificial kidney system and the traditional hemodialysis mode, we successfully developed a low-cost and portable hemopurification device for short daily hemodialysis. The feasibility and effectivity of this device were verified by experiments with porcine blood. It was found that the clearance of urea and creatinine can reach more than 58%.

Keywords: Hemopurification device, artificial kidney, porcine blood, daily hemodialysis, hemofiltration.

INTRODUCTION

Hemopurification was first presented and applied to the clinic by Hass in 1923 [1], and still emerging with extensive applications of blood purifications. Hemopurification containing hemodialysis, hemofiltration, ultrafiltration, hemoperfusion etc. It is comprehensively used to cure poisoned patients and patients with uremia. At the same time, the therapy device called artificial kidney is receiving major intention by bioartificial renal investigators.

The frequency of hemodialysis was established as three times a week in the 1960s [2] and has been widely accepted and sustained for logistical, pragmatic, and economic reasons in the past fifty years. The intermittent hemodialysis (IHD) method has been widely accepted and used in hospitals, although it has some complication and deficiencies on pragmatic values together with lower the life quality of dialysis patients. However, hemopurification has some new progress in treatment concept and clinic treatment content in recent years. For a better treatment of patients with uremia, short daily hemodialysis (DHD) is recommended, and it has an increasing interest in using more frequent dialysis for long-term treatment with extensive advantages [3, 6]. Clinical data consistently have shown improvement of life quality of patients, better control of blood pressure, reduction of medications including erythropoietin (EPO), healthier nutrition and most important low cost of treatment. Short daily dialysis has been used for more than 20 years and nocturnal dialysis has been used since 1995[3, 7]. Despite the daily dialysis and its advantages, large-scale hemodialysis machines are still dominating in clinical hospitals. Considering that agitations, we tried to the extent a low cost and capable hemopurification device (HPD) that can meet the demand of frequent dialysis, it has the potential to improve the quality of life of patients with alleged clinical/hospital applications as well as more economical for patients and healthcare providers.

In this work, we propose a low cost and proficient device combined hemodialysis and ultrafiltration. It is based on short daily hemodialysis (DHD) protocol. Thus, application of hemofiltration and its device prototype's design, we reduce the consumption of pure water and dialysate abruptly. To evaluate the function of the prototype and its investigative device presentations, a rigorous porcine blood trial in-vitro is carried out for verifying the clearance of urea and creatinine. The device demonstrated the stability and reliability of the whole purification experiments.

DESIGN OF THE DEVICE

The HPD dimensions are 40 × 35 × 50 cm and weigh almost 20kg, makes the device portable. Fig. 1a shows the schematic of internal components of the device. The C8051f040 is the master microcontroller that receives and process the signal from the sensors and C8051f320s sub-processing units. The two sub-processing units C8051f320s are the slaver microcontrollers that received and process the signals from the balances (A-B). An isometric view of the device is shown in Fig. 1b. The outer shell is made of acrylonitrile butadiene styrene copolymer (ABS). Three peristaltic pumps (12-volt DC step motors YZ15, PreFluid, China) are placed around the HPD. The three pumps are devoted to a blood pump, dialysis pump, and ultrafiltration pump, respectively. As Fig. 1b shows, the left one is the blood pump, which drives blood flow, the one on the right-side is the ultrafiltration pump, which drives ultrafiltrate flow and the one at the back-side of the device is the dialysis pump, which drives replacement fluid flow. The dialysis pump and the blood pump push the replacement fluid and blood into the dialyzer, respectively, while the ultrafiltration pump pulls the corresponding waste out. The flow rate of the pumps can be adjusted over a range from 10 to 250ml/min. The hemofilter is FX80 (Fresenius, Germany, K_{uf} 59.0ml/h/mmHg, available membrane area 1.5m^2, and sieving coefficient for albumin 0.001).

The two electronic balances (WT150001X, WANT, China) with weight precision of 0.1g are used to evaluate replacement fluid and ultrafiltrate. Once it starts, the flow rate of the ultrafiltrate is constant while the flow rate of replacement fluid is fluctuating. By considering the replacement of fluid and ultrafiltrate repeatedly we can access both flow rates then lastly programming it on automatically mode adjustive, the dialysis pump is balanced to the blood volume which is constructed on PID algorism [8]. In conclusion, weight balance control allows adjusting the balance of blood volume in real time through the method of feedback, or error accumulation. The costs on the shell, pumps, scales, and control circuitry are about 6000CNY, 2700CNY, 2800CNY, 5500CNY, respectively, which is about 17000CNY in accumulation, compelling the costs of labor and functionality improvements is consideration, the price of device may not be more than 50000 CNY, which may be more likely domestically accepted, as most of the dialysis machines are more than 100000CNY according to quote online [9, 11].

EXPERIMENT AND RESULTS

To verify the device operates as an artificial kidney, porcine blood purification experiments in-vitro were conducted. Figure 2a depicts the schematics of the pipeline, the pre-dilution mode is adopted. Blood mixes with the replacement fluid at the T-branch pipe, then inflows the hemofilter. The purified blood returns to the blood container, and the ultrafiltrate contains a high concentration of toxin which dissociated from blood driven by the ultrafiltration pump. Two pots are placed before blood flowing into the hemofilter and returning to the container in order to collect bubbles.

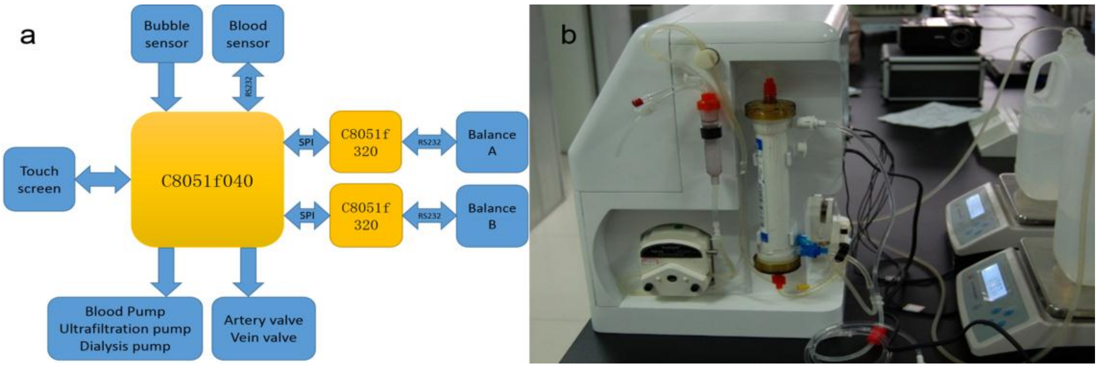

Figure 1. The structure of the device. **a** The schematic. **b.** The isometric view of the device.

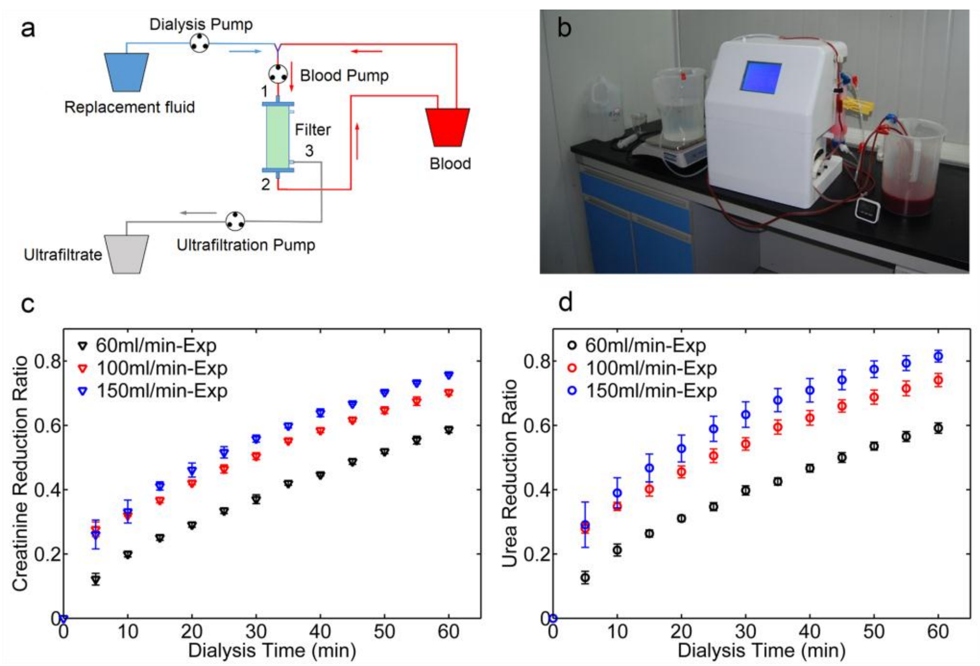

Figure 2. The device works as an artificial kidney. (**A)** A simplified schematic description of the device experimental setup. (**B)** The overall appearance of the device experimental setup. **(C)** The reduction ratio of creatinine (n=3). (**D)** The reduction ratio of urea (n=3).

The hematological constants of porcine blood are close to human's blood, as the specific gravity of whole blood of human and hog are 1.05-1.06 and 1.005-1.06, and both the relative viscosity are 4-5 [12, 13]. Porcine blood was obtained from the slaughterhouse. Traditional citrate phosphate dextrose adenine (CPDA, every 1000ml CPDA contains 3.27g citric acid, 26.3g tri-sodium citrate, 2.22g sodium dihydrogen phosphate, 31.6g glucose, and 0.275g adenine) nutrition anticoagulant solution is used to prevent blood clots, every 140ml CPDA is available for 1000ml blood.

High concentrations of blood urea nitrogen (BUN) and creatinine are significant symptoms of patients with uremia, therefore, its mean/median concentration of BUN and blood creatinine is 2.3±1.1g/L and 136.0±46.0mg/L, respectively [14]. In this study, 1L of porcine blood is interfused with 3432mg urea and 320mg creatinine, which is used as for substitute of human blood with uremia. Normal saline (0.9%wt) mixed with CPDA, the proportion mentioned above is used as replacement fluid. To evaluate the adequacy of treatment, a urea reduction ratio (URR) is often used (hemodialysis is considered adequate when URR>65%). The reduction ratio is calculated as follows [15]:

$$D = 1 - C_t / C_0 \qquad (1)$$

Where D refers to reduction ratio; C_t and C_0 are concentrations ($\mu mol / L$) at time t and the initial moment. At the beginning of the experiment, the pipeline is pre-rinsed with replacement fluid for few minutes to exhaust gas in the pimp line and hemofilter, the replacement fluid will flow-in from the inlet 2 and 3 and flow-out from outlet 3 by adjusting the rotation directions of the pumps. After pre-rinse, while the experiments, the flow directions are shown in Figure 2a. Different blood pump rates are followed: 60ml/min, 100ml/min, and 150 ml/min, while the ultrafiltration pump is set at a constant rate of 30ml/min. The fresh porcine blood is sampled every 5 minutes to obtain concentrations of urea and creatinine, and the corresponding reduction ratios (RR) are calculated. The experiment lasts for 60 minutes, 1.8 L replacement fluid is consumed approximately and 13 samples are obtained in the end. In the same conditions, the trial of each rate is repeated 3 times. No significant change of blood volume is observed at the end of each experiment. All the samples are centrifuged to get serums and then measured the concentration of urea and creatinine with an automatic biochemical analyzer (AU480, Beckman Coulter, USA). The concentration of urea is measured with GLDH (glutamic dehydrogenase) kinetic method, the colorimetric wavelength is 340 nm, and the concentration of creatinine is measured with the picric kinetic method, the colorimetric wavelength is 510 nm.

Table 1. Urea and creatinine reduction ratios at different blood pump rates

Blood pump rates (ml/min)	Urea RR	Creatinine RR
60	0.5917 ± 0.0159	0.5869 ± 0.0097
100	0.7409 ± 0.0205	0.7025 ± 0.0088
150	0.8153 ± 0.0181	0.7579 ± 0.0027

The creatinine and urea reduction ratios changed over time are shown in Fig. 2c and 2d. Table 1 shows the final reduction ratio when the rate of blood pump exceeds 100ml/min, URR is greater than 65%. Compared with normal artificial kidneys, the price of our machine is less than half the normal ones. The water consumption is greatly decreased, and the dimensions and weight are available for portability

CONCLUSION

In conclusion, the experimental results when the rate of blood pump exceeds 100ml/min demonstrate a sufficient dialysis according to the urea and creatinine clearance standards. In addition, increasing the blood pump rate will promote the reduction ratio of urea and creatinine, as reduction ratios increase about 30% when blood pump rate increases from 60ml/min to 150ml/min. The device is efficient for hemopurification. Furthermore, its light weight and small size volume of dialysate make it possible to achieve daily treatment at home. The device based on the concept of DHD, and protocol of hemofiltration seems to be efficient, portable and economical.

ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (Nos. 51276179, 51476160 and 51528601).

Conflict of interest

The authors declare that they have no conflict of interest.

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