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Development of an Integrated Salt Cartridge-Reverse Electrodialysis (RED) Device to Increase Electrolyte Concentrations of Human Blood Flow to Power Biomedical Devices

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Abstract:

Emerging technologies in nanotechnology and biomedical sciences have led to an increase in biomedical implantable devices including cardiac pacemakers, artificial organs, drug pumps, and sensors. These devices require continuous stable and reliable power to operate, which creates the demand for the need to find a safe, reliable, and stable power source. A promising avenue for a power source for these devices is a miniaturized reverse electrodialysis (RED) biopower cell design that utilizes the salinity differences between bloodstreams that flow inside the human body. Initial results of the RED system demonstrate that higher gradient salinity differences between streams lead to a higher power density. In order to generate this higher salinity gradient, an additional salt cartridge consisting of polysulfone hollow-fiber membranes was integrated into the RED system. This study explores the effects of different system parameters, including the number of hollow fiber tubes and the volume of the cartridge, on the normalized salt concentration pickup to achieve the optimum design for the integrated salt cartridge. Preliminary results indicate that a 50% increase in the power density output of the RED power cell could be achieved by using a 100 g/L solid salt reservoir in the *in-situ* salt-pickup cartridge. The integrated salt cartridge will be further miniaturized to optimize the salt concentration pickup and to develop a compact and implantable design by utilizing 3-D printing and nanolithography.

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1. Introduction/Background:

Implantable biomedical devices are increasingly common due to advancements in nanotechnology and biomedical sciences. Biomedical implantable devices, including cardiac pacemakers, artificial organs, drug pumps, and sensors require continuous stable and reliable power to operate, which creates the demand for the need to find a safe, reliable, and stable power source. The power consumption on these devices is relatively low, an example would be a cardiac pacemaker, which requires a power input ranging 8-400 μW that is provided by a Lithium-ion battery [1]. Although practical and widespread on paper, a previously reported article revealed that the average life span of these batteries is ranged from six to nine years [2]. Furthermore, when the battery is dead, a surgical operation is needed for the replacement, which comes with risks for the patient; approximately 1-5% of people experience infections and bleeding, and 9% experience the lead moving [3,4]. Also, battery replacement surgeries put a heavy burden on the medical system as well, considering that pacemaker replacement surgeries currently occupy more than 25% of all implantation surgeries performed nationally [5]. Another interesting but rather improbable aspect about the pacemaker batteries' hazards was also identified to be revealed in the post-mortem stage of the patient as a previous study showed that explosions are frequently observed in the cremation of bodies with pacemakers still attached to them [6]. Moreover, the advancements in polymeric-based pacemaker batteries could yield even more serious explosions in the future. Thus, when all the hazardous elements are considered, an alternative method of powering up these medical devices is urgently needed.

Considering the lower power consumption demand of these implementable devices, several efforts have been previously made to develop alternative power sources that aim to increase the longevity of the biomedical device operation. One approach was to harness solar energy to be potentially converted into electrical power [5]. Although sufficient energy could be achieved with this technique, a major drawback of this approach is the incompatibility of solar panels with the human body. Another study shows a newer approach of harvesting energy from the everyday movements of the human body by kinetic and thermal energy harvesters. Even though it was shown that the human body exhibits enough kinetic energy to be harnessed to power up devices in the lower energy range, the unstable power output that shows fluctuations could cause unpredictable and sudden interruptions, making them unstable and unreliable sources of power for the implantable biomedical devices [7,8]. Lastly, biological-based approaches including enzymatic and microbial fuel cells were also presented as promising power production techniques that aim to harness the biological species innately found in the human body [9]. Although numerous studies have shown that they could produce enough power to be independent power sources, the major challenge is the short lifetimes due to enzyme instability and degradation. The disadvantages in all the previous approaches mean there is not a viable long-term solution for replacement batteries.

Reverse electrodialysis (RED) is a salinity-gradient energy capturing technique where the potential energy of mixing is harnessed through a series of ion-exchange membranes and electrodes [10]. It is a promising, clean way of harvesting energy where Gibbs Free Energy of Mixing of two streams containing different salinities can be converted to usable electric energy [11]. Its overall efficiency and applicability on the hyper-saline conditions are also major advantages when compared with the other salinity-gradient energy methods (e.g., CapMix and PRO), allowing the use of natural water sources including seawater and brackish water [12]. Moreover, efforts have already been made to produce clean energy on a large scale, as seen in the Netherlands powerplant that uses natural water sources to produces up to 1 MW of power [13]. Another advantage of RED is that minimum to no energy input is needed to harness power out of aqueous sources. A previous study showed that a net power density of 1.2 W/m^2 was achieved by only exploiting seawater and river water as the RED streams [14]. Although the development of the RED technology is mostly based on an increased number of stacks to maximize the power density, miniaturized approaches have also shown promising areas of application, as shown in a recent study from the Hestekin lab where biological fluids were used as a source to produce power within our own bodies [15]. It is explored in the same study that the natural ion gradient between two kidney bloodstreams that is maintained through the complex process of removing waste from the body as urine could be used in the favor of energy production via a miniaturized RED power cell. The disadvantage of the proposed approach as a power source; however, is the comparatively small concentration gradient found naturally throughout the body streams. Nevertheless, it is observed that enlarging the salinity gradient in between the two physiological streams has led to a significant increase in the power output of the power cell. Therefore, it is essential to find a solution to tweak the salt concentration of the streams going into the RED power cell, to increase the power output well enough to deliver enough power for the biomedical devices.

In this study, an integrated salt pick-up cartridge and a RED power cell device were designed and tested to potentially power an implantable device. It is aimed that the natural salt concentration gradients found in the body could be boosted with an *in-situ* salt cartridge, before going through the RED power cell to power devices with larger power consumptions, i.e., a pacemaker. A salt cartridge will be integrated with the RED device to create a larger gradient and this larger gradient will then be converted into power which has the potential to power these devices. This study explores the parameters necessary for the salt cartridge to achieve the theoretical salt pickup required.

2. Experimental

3.1 Materials

Sodium chloride (NaCl, ACS reagent ≥99%) was acquired from VWR USA (Radnor, PA, USA). Platinum electrodes (gauze, 100 mesh 99.9%) were obtained from Sigma-Aldrich (Sigma-Aldrich Co., St. Louis, MO, USA). Titanium wires (0.01 inch in diameter) were acquired from Alfa Aesar (Haverhill, MA, USA). Cation exchange membranes (Fumasep FKL-PK-130 CEM, 130 μm) and anion exchange membranes (Fumasep FAA-PK-130 AEM, 130 μm) were both purchased from Fumatech BWT GmbH (Bietigheim-Bissingen, Germany). Mentioned membranes have been found to be effective for RED systems because of their lower thicknesses and higher permselectivity performance [16]. All solutions were prepared using Milli-Q water (18 MΩ cm).

3.2 Preparation of Salt Cartridge and Hollow-Fiber Membranes

The salt cartridge consisted of polysulfone hollow fiber membranes, which were made in-house. Solid polysulfone and N-methyl-pyrrolidinone (NMP) are mixed and rolled for 4-5 days for full incorporation and to get rid of any bubbles existing in the viscous solution. Hollow fiber casting was made possible by incorporating the main polymer solution and the bore solution, into the spinneret. While the polymer solution creates the outer shell for the fibers, the bore solution that is introduced to the polymer in a geometry that would create the hollow layer inside the fiber tubes by dissolving the polymeric content. The solution flow rates and pressure are then optimized to achieve the correct fiber consistency that is then collected on the spinneret inside the fiber water bath. The fibers formed are then collected onto a spinning roll and soaked in 70% ethanol solution to further eliminate the excess solvent on the surface until use.

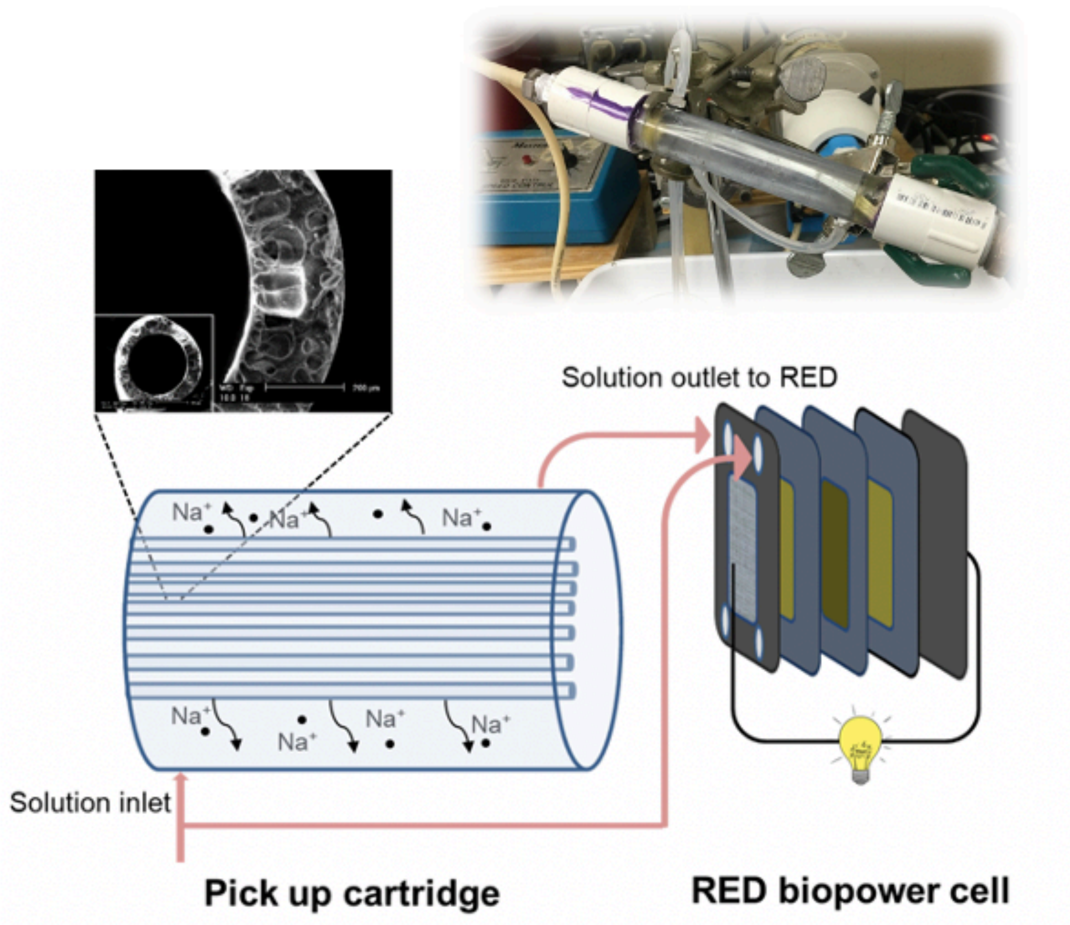


Figure 1. Schematic representation of the salt cartridge-RED power cell setup.

Polysulfone hollow-fiber membranes were utilized to allow ion movement from the cartridge source into the RED inlet solution (Figure 1). The hollow-fiber membranes are porous enough to allow the flow of Na^+ ions. The salt cartridge was integrated with the RED biopower cell to boost the power density output. Different cartridge salt concentrations and solution flow rates were tested to optimize the preparation of the salt cartridge.

The number of hollow-fiber tubes and hold-up volume of the cartridge were also tested to optimize the salt-pickup performance. The cartridge's purpose is to increase the salt gradient found naturally in the body so that this gradient can be used in powering implantable biomedical devices.

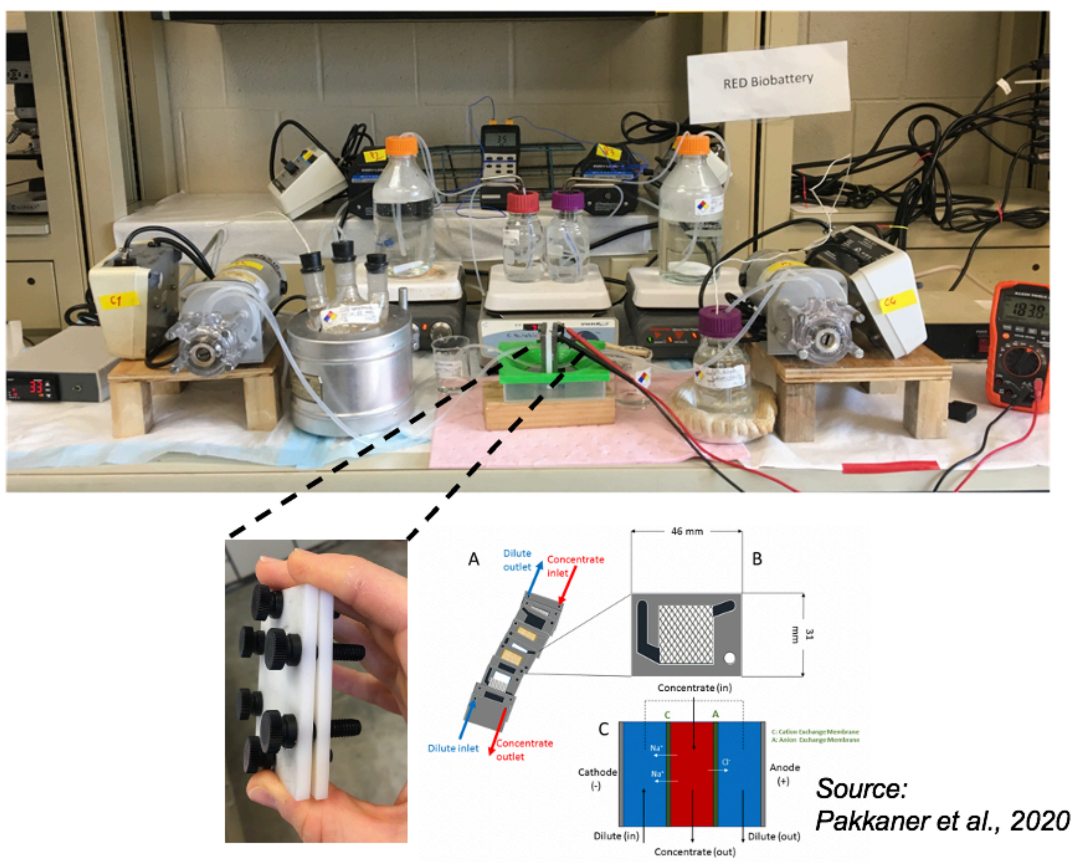


Figure 2. RED experimental set up and the schematic representation of the RED power cell.

3.3 RED Device Set-Up

The RED device was a 3-D printed miniaturized RED power cell that was used as previously published [16] (Figure 2). The dilute was mimicked from the renal vein NaCl concentration (7.2 g/L) for the RED stream. The salt concentration of the concentrate stream was varied to determine the effect the gradient had on power density output. Physiological temperature (37°C) was maintained with PID control.

3.4 Statistical Analysis

As soon as the output data that explains the influence of the selected parameters on the salt-pickup performance is attained, a statistical model which aims to predict the theoretical possible power density output for the final boosted stream salt concentration is planned to be constructed (Figure 3). The model equation is planned to be derivated with Minitab Statistical Software (Minitab Inc., PA, US) using the ANOVA function.

	Device Parameters		
Power Density Outputs	Number of Tubes	Flow rates	Volume
Pacemaker			
Sensor			

$$Y = C_1 (\# \text{ of Tubes}) + C_2 (\text{Flow rate}) + C_3 (\text{Volume})$$

Figure 3. Prospective model parameters and template.

3. Results and discussion

3.1 Salt Pickup Analysis

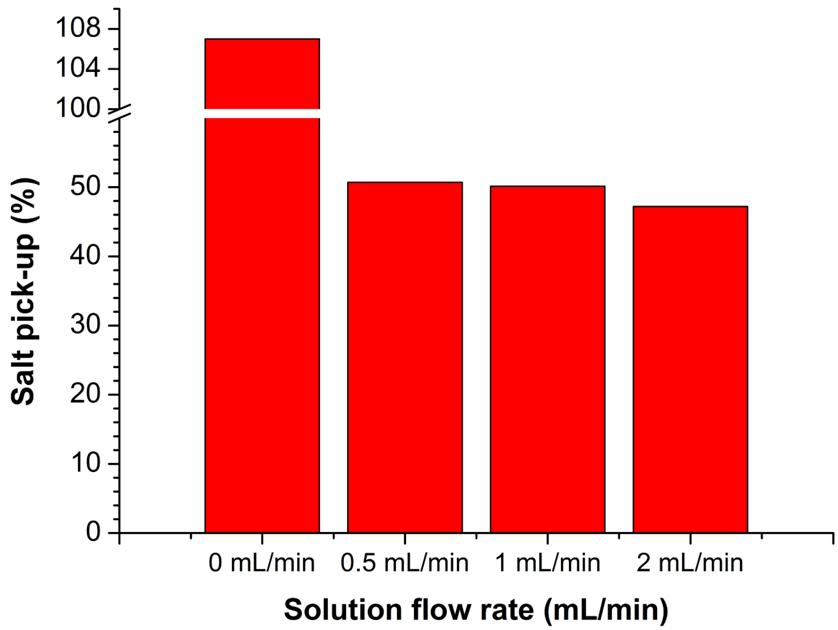
To increase the power density created from a RED device, the gradient between the two body stream concentrations has to be increased. This study looked into increasing the concentration of salt in one stream with the salt cartridge by changing different parameters of the device and solutions. The average pickup of salt was the average amount of increase in the salt concentration in the stream and was reported in percent or concentration units.

Table 1. Salt Pickup for Varying Cartridge NaCl Concentrations

Solution NaCl Concentration (g/L)	Cartridge NaCl Concentration (g/L)	% Average Pickup
~0 (Deionized-water)	100	<100
7.2	20	14.08 ± 7.3
7.2	100	51.07 ± 24.3

*Q_{soln}: 1 mL/min, #fibers: 10, $V_{cartridge}$: 30mL, n=3.

Hollow fiber diffusion is feasible for picking up salt *in situ.* As the gradient increased between the salt concentrations, the average pickup percent also increased. While literature in this area is limited, it is comparable to a dialysis system. Dialysis uses hollow fibers to transport ions from the dialysate to blood or vice versa using diffusion across the ion gradient and convection [17]. Previous studies show that an increase in sodium concentration in an external solution such as dialysate will show an overload of sodium concentration in the blood [18].



* C_{soln}: 7.2 g/L, C_{cart}: 100 g/L, #fibers: 10, $V_{cartridge}$: 30mL.

Figure 4. Salt Pickup vs Solution Flow Rate

The stagnant case showed higher pickup while decreasing with an increasing flow rate. The decrease between the salt pickup for the 0.5 mL/min and 2 mL/min was minimal which is a promising trend as testing continues towards flow rates found in the body. This data shows that the amount of salt picked up is tunable with different flow cases.

The pressure was induced to transport ionic species to the solution. A tremendous pickup was achieved in this testing. However, when compared to the saturation limit for salt in water, there is still much room for improvement. There was a volume increase that varied due to the ultrafiltration. A lower K_{UF} membrane will be tested to produce more control over the diffusive transport. The lower K_{UF} membrane will prevent fewer water molecules to flow through into the cartridge and instead just NaCl ions will flow into the cartridge.

Table 2. Pressurized Fiber Testing

Solution NaCl concentration (g/L)	**Cartridge NaCl concentration (g/L)**	**Intermembrane Pressure (IMP) (psig)**	**K_{UF} (mL/h.mmHg)**	**Final solution NaCl concentration (g/L)**
~0.7(Deionized-water)	7.2	2	17.5	7.4 ± 2.97

*** $C_{NaClsat}$: 357 g/L, @25C**

There was a three-fold increase in power density when there was a 50% salt pickup. It has been reported that an average of 60% increase in PD is achieved with a 4-fold increase in solution molarity [19]. There is still room for improvement in the salt cartridge which would allow a higher salt concentration. This increased gradient would allow a higher power density to be achieved and theoretically power a pacemaker.

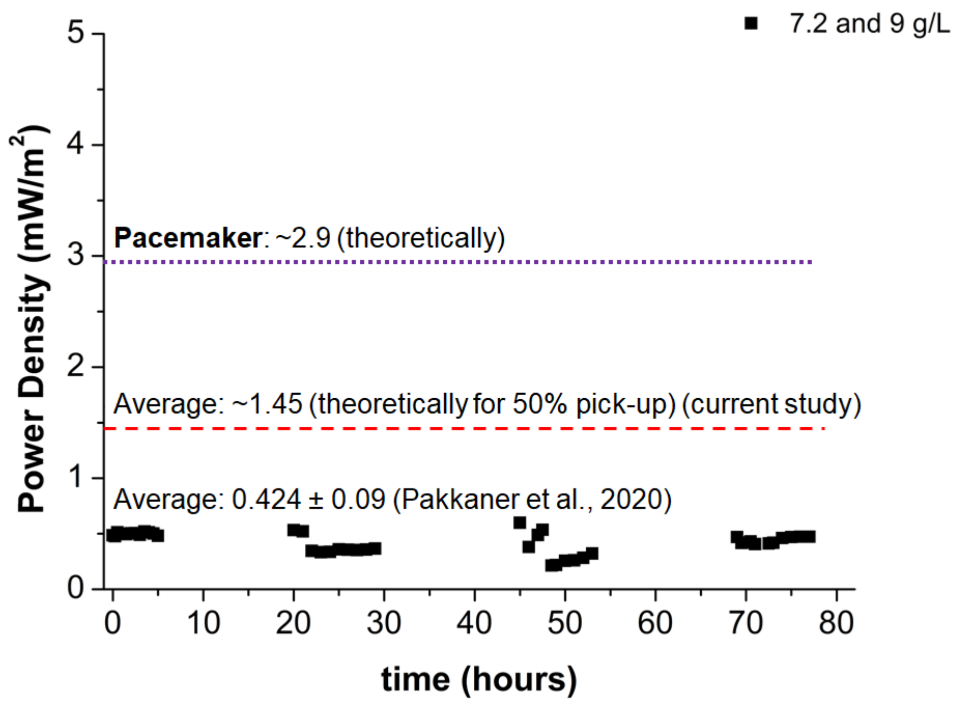


Figure 5. Overall comparison of power density values achieved vs. desired

4. Conclusions

A miniaturized salt cartridge was built and parameter effects on the pick-up performance were discussed and analyzed. Higher concentration gradients achieve a higher average salt pickup percent in the cartridge. The stagnant flow rate has the highest achieved salt pickup percent. This study demonstrated that it was possible to tune pick-up salt concentrations to desired concentrations by changing the flow rate of the stream coming into the device. Preliminary results showed that 50% pick-up performance could be achieved with moderate NaCl concentrations such as 100 g/L. An increase in concentration could lead to a higher pickup performance. Diverting the solution flow into the fibers and adding TMP resulted in tremendous pick-up. However, the K_{UF} needs to be discussed as a lower K_{UF} membrane could allow for a higher salt pickup due to fewer water molecules flowing into the cartridge.

5. Future Work

Ongoing studies focus on the long-term capabilities of salt cartridge performance and influence on the RED power output. In the future, 3D printing will be further utilized to minimize and integrate the salt cartridge design. Further optimization of the salt cartridge to further increase the salt gradient between streams should be explored. Continued work is happening on the theoretical model of power density output using device parameters to optimize salt cartridge.

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