النمذجة العددية والدراسة التحليلية للرحلان الكهربائي للمحلول الملحي داخل النموذج الأولي للكلية المزروعة

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الملخص

تعتبر كلية الإنسان من أهم أعضاء جسم الإنسان وتؤدي وظائف عديدة ولها تأثير كبير على عمل باقي أجهزة الجسم البشري، أصبحت الكلى الاصطناعية والقابلة للزرع تقنية واعدة ومحتملة لتعويض الكلى التالفة. في هذا البحث، نقدم نموذجاً أولياً لكلية قابلة للزرع تم تصميمها باستخدام Solidworks. يتيح لنا النموذج الأولي للجهاز المقترح إجراء فصل للجسيمات باستخدام الرحلان الكهربي مع مجال كهربائي خارجي. تم تصنيع النموذج الأولي النهائي باستخدام الطباعة ثلاثية الأبعاد ويتم إجراء تجربة في المختبر لفصل الجسيمات باستخدام محلول ملحي، بالإضافة إلى المحاكاة العددية لتدفق المحلول تحت تأثير المجال الكهربائي باستخدام COMSOL Multiphysics.

توضح النتائج في المختبر أنه يمكن استخدام الجهد الكهربائي لفصل الأيونات المشحونة تحت تأثير قوى التحيز الكهربائي إلى القطبين المعاكسين لشحنها. كانت المحاكاة العددية للتصميم المقترح وطريقة الفصل باستخدام COMSOL Multiphysics قادرة على إظهار اختلاف في مسارات الجسيمات مع وبدون مجال كهربائي مطبق.

الكلمات المفتاحية: الكلية القابلة للزرع، الرحلان الكهربائي، التجارب المختبرية، برنامج الكومسول.

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Numerical Modeling and Analytical Study of the Electrophoresis of Saline Solution within Prototype of an Implantable Kidney

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Abstract

The human kidney is one of the most important organs in the human body. It performs many functions and has a great impact on the work of the rest of the organs. Artificial and implantable kidneys become a promising and potential technology to compensate damaged kidneys. In this paper, we are presenting a prototype model of an implantable kidney that is designed using Solidworks. The proposed prototype device enables us to conduct a particle separation using electrophoresis with an external electrical field.
The final prototype is fabricated using 3d printing and an In Vitro experiment of particle separation is conducted using a saline solution, in addition to numerical simulation of solution flow under influence of an electrical field using COMSOL Multiphysics.
In vitro results illustrate that electric potential can be used to separate the charged ions under the influence of the electric bias forces to the opposite poles to charge them. The numerical simulation of the proposed design and separation method using COMSOL Multiphysics was able to show a difference in particle trajectories with and without applied electrical field.

Keywords: Implantable Kidney, Electrophoresis, In Vitro, COMSOL Multiphysics.

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Introduction

Urinary system is a group of organs that filter excess fluids and other substances from the bloodstream as substances are filtered out of the body in the form of urine. The urinary system works with other body systems in maintaining the balance of water and electrolytes in the body. The kidneys are one of the main organs for achieving acid-base balance. The kidneys may often be exposed to diseases that make them unable to carry out their vital functions. These diseases vary in type, severity, and treatment methods, but the most dangerous is kidney failure in which the patient needs care and compensation for the work of the kidney either with a natural kidney from a donor or blood purification using therapeutic devices such as hemodialysis and peritoneal dialysis [1].

The aforementioned two devices are considered external technical solutions that require time and effort on the part of the patient and the medical staff. Moreover, these devices may cause physical and psychological fatigue for the patient, as the patient needs dialysis at least three times a week, and this frequency is subject to increase according to the patient’s health condition [2]. In addition to the previous solutions, researchers in the field of medical engineering have developed a portable dialysis device. This represented an alternative solution that is tiring in terms of weight and permanent attachment to the patient's body through the jacket that contains it [3]. In the same context, scientists and researchers in medical engineering are tending to develop an alternative kidney that can be implanted and approach the best to the function of the natural kidney.

Many researchers have studied the principles of particle separation and worked to prepare these techniques for use in biological applications such as isolating unwanted particles from the biological medium or separating species according to their different characteristics. Several principles of separation are normally used including optical, acoustic, magnetic, and electrical[4]. The electrical separation technology is advantageous due to low sample consumption compared to other methods, besides the low cost, fast analysis, and high productivity[5].This principle was used in biological applications to separate platelets from the other components of the blood and was also used to divide blood into red and white blood cells, as red blood cells are most probably generate a large electrical separation force compared to white blood cells, and this helped in the separation process[6].Furthermore, this principle was used to distinguish different cancerous cells from the bloodstream bydesigning a separation chamber with one entrance and two outputs. Different voltage values were applied and the variation in response of both normal and cancer cells was noticed which leading to the feasibility of the use of this technique in the field of breast cancer[7]. The studies also dealt with the use of this technique in separating ions according to the difference in charge. A separation chamber containing two opposite electrodes on both sides of the path with one inlet and two outlets Y was designed. This permitted to study of the influence of several parameters. It is worth mentioning that the effect of these parameters was tested experimentally without explaining the reason for using the applied voltages and concentrations values[8].

In this paper, we are presenting a prototype model of an implantable kidney that is designed using Solidworks. The proposed prototype device enables us to conduct a particle separation using electrophoresis with an external electrical field. The final prototype is fabricated using 3d printing and an In Vitro experiment of particle separation is conducted using a saline solution, in addition to numerical simulation of solution flow under influence of an electrical field using COMSOL.

Methods

1. Prototype design and separation circuit

We designed a prototype that offers the ability to inject the ionic fluid, taking into account the possibility of applying electrical field using copper coils from both sides of the main channel, so that copper coils are inserted from the side externally to allow replacement in the case of damage without causing harm to the model and (Figure 1) shows a cross-section of the frontal and lateral profile of the model.

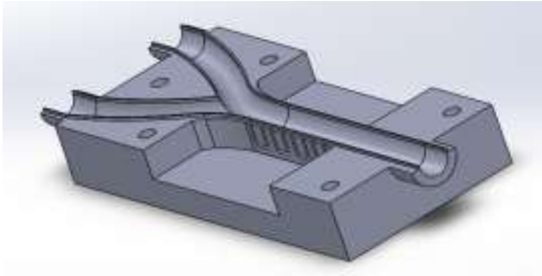

Figure 1. Prototype of implantable kidney design using Solidworks.

The final model was fabricated using LK1+ 3D printer with PolyLacticAcid (PLA) printing material which its physical and chemical properties don’t affect the saline solution flow.The final separation circuit consists of a Y-shaped separation chamber, a 20ml syringe, a DC voltage source with variable values ranging from zero to ten kV, and containers for collecting liquid after separation as shown in (Figure 2).

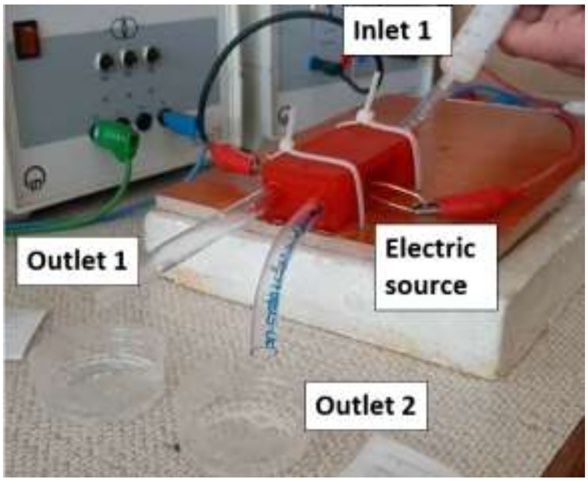

Figure 2. Separation device with the saline solution pumping and applied external electric field.

The previous studies focused on the electric field rather than the direct contact of electrons with the ionic liquid [9].We suggested using any saline liquid that contains positive and negative ions to carry out the test. A solution of sodium chloride salt was prepared with distilled water at a concentration of 50%[10]. A manual syringe was used to inject the test liquid into the separation chamber, taking into account that the flow velocity was kept almost constant during the injection and the application of high voltage. Two values of 8 kV and 10 kV were used.

2. Numerical simulation using COMSOL

To perform a numerical simulation of the proposed system, we are using COMSOL Multiphysics 5.4. We imported the 2D sketch of the Top view of the proposed model. The COMSOL model consists of type parts according to physical study type, the first part represents the laminar flow study of saline solution with one inlet with pressure equals 105 Pa and two outlets with zero pressure and NaCl (liquid) is used as medium material, the boundary condition was set as no slip on the channel walls, and the physical property of fluid was chosen as incompressible flow.

The second part acts as an external coil to generate an electrical field, where an electric current study is used with two 10KV and -10KV electric potentials using two positive and two negative poles as shown in (Figure 3). The used material of the electrical part is copper with relative permittivity equals to 80, Reference resistivity of 1.68 Ω·m and Resistivity temperature coefficient equals 0.00386 1/K.

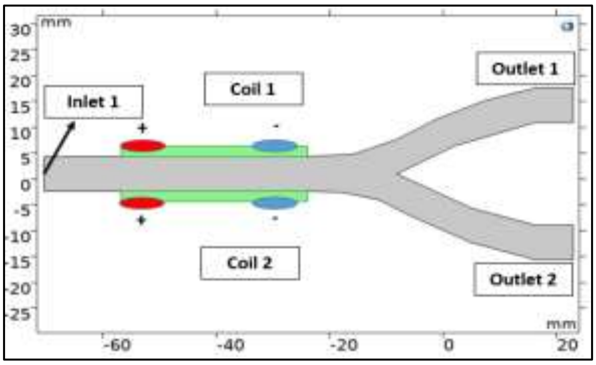

Figure 3. COMSOL model with components.

The order of finite element was set to P1 + P1, the default setting of COMSOL Multiphysics. The component was meshed by the physics-controlled mesh at the default fine level with 3276 elements in total and 2096 vertices.

Results and discussion

1. Results of silver nitratereagent

From a chemical point of view, chloride can be detected in its solutions using silver nitrate, where we have a white precipitate in the form of a fixed ring. It is also possible to use litmus paper, which is coloured in different colours in acid and alkaline solutions. According to what we mentioned, the analytical chemical method is used to test the results of the separation.
After pumping the saline solution with 50% of concentration in inlet using a syringe and applying 10 kV on electrodes. The resulting samples from both outlets were collected in separated glass beakers.
After that, we used silver nitrate with the resulting samples to detect the type of separated particles. The sample on the

positive outlet (outlet 1) side contains a high concentration of chlorine ions, while it contains a lower level of sodium ions. In contrast, the samples on the negative outlet (outlet 2) contain a high concentration of sodium ions which is turbid as shown in (Figure 4).

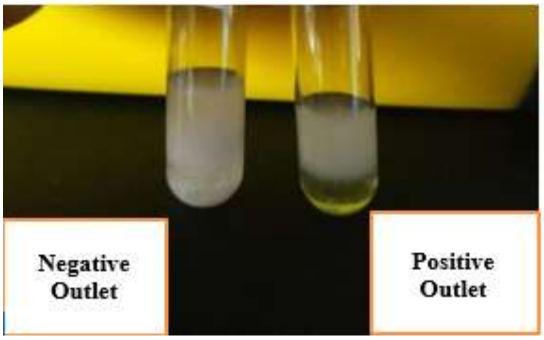

Figure 4. Results of using silver nitrate with 10 kV resulting samples.

The turbidity is related to the presence of sodium, while the ring or the white precipitate of a fixed shape for the solution is related to the presence of chloride. The relationship between the applied voltage and the detection rate was clarified in (Figure 5) where the voltage increases, the separation between the electrolytes increases, and the ability to detect the results chemically increases too.

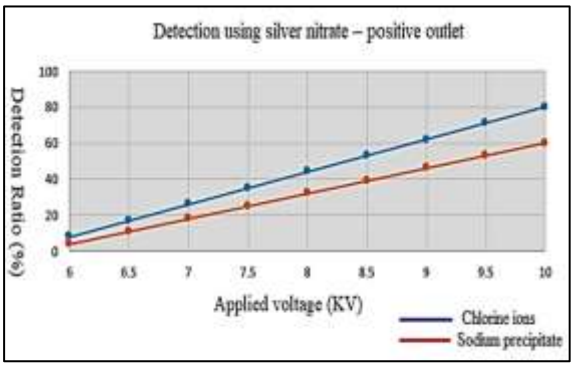

Figure 5. The relation between detection outcomes in positive outlet and applied electric voltage.

2. COMSOL Multiphysics results

The simulation of COMSOL using the same prototype design, solution and external electrical field comes to emphasize more the results that we have seen In Vitro work. By using particle tracing of sodium in the same saline solution, with a particle size of 1.4 µm and density of 971 kg/m3, and conducting a time-dependent study in COMSOL with time range equals 0-10 sec without electrical field. We are able to see a higher flow rate of particles in the upper chamber (outlet) as shown in (Figure 6).

In contrast, by activating the external electrical field with 10KV we can note a clear difference in particle trajectories where distributed equally in both outlets as shown in (Figure 7).

The results are not so identical to In Vitro outcomes, but in COMSOL we were able to understand the phenomenon in a numerical way, which could provide in the near future a precise tool to conduct a full simulation process of an implantable kidney.

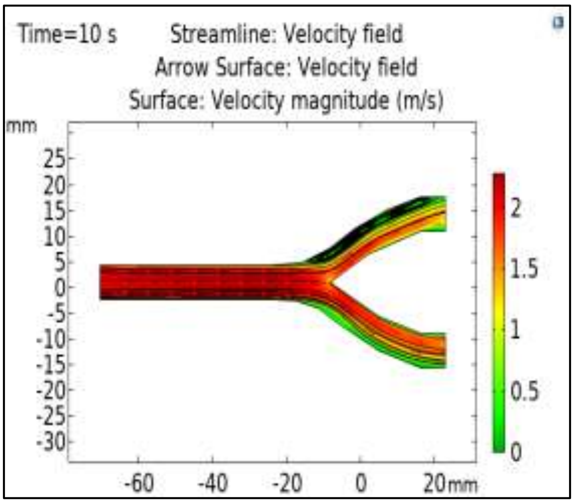

Figure 6. Particles trajectories of COMSOL model without applying electric field.

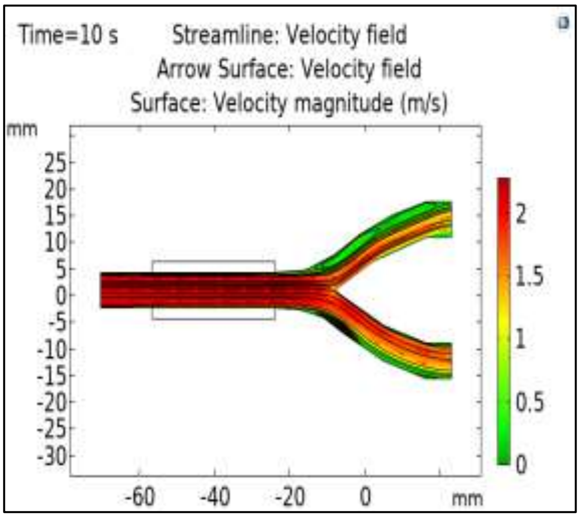

Figure 7. Figure 6. Particles trajectories of COMSOL model after applying electric field in the black rectangle.

Conclusion

This paper dealt with designing artificial kidneys using 3D printing and electrophoresis. The results show that it is possible to use the Solidworks program in designing the three-dimensional structure of the engineering models and export them in a 3D-printable form, and this method has proven its effectiveness in the proposed separation device.

In vitro results illustrate that electric potential can be used to separate the charged ions under the influence of the electric bias forces to the opposite poles to charge them. Where the concentrations of electrolytes in the samples after separation processes increases according to the applied electrical voltage.

The numerical simulation of the proposed design and separation method using COMSOL Multiphysics was able to show a difference in particle trajectories with and without applied electrical field. Those results encourage us in the near future to have a more comprehensive simulation of the implantable kidney using COMSOL which according will enhance In Vitro positively.

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