Eliminating Vascular Obstruction in Myocardial Infarction by Accelerated Ferromagnetic Microrobot

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Research Article

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Eliminating vascular obstruction in myocardial infarction by accelerated ferromagnetic microrobot

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Abstract:

Background: vascular obstruction by clots is one of the main reasons of cardiovascular disease such as myocardial infarction. There is a short time, less than 6 minutes, to establish the blood flow, especially in vital organs. While conventional techniques are not very fast and effective, current micro-robots have inherent limitations such as being slow to achieving this goal.

Objective: There is a strong requirement to develop microrobots with new principles that can quickly eliminate clot blockage in the vascular. The aim of this study is to evaluate, *in-vitro*, the efficiency of accelerated ferromagnetic micro-robots in destroying blood clots in an artificial vascular precipitately.

Methods: An artificial graft with a diameter of 10 mm were used as the vessel. Blood clots with various lengths (5*10 and 10*10 and 20*10mm^3 (dimeter*length)) are formed inside the graft. Microrobots made of steel with a length of 1 mm and a width of 0.05 mm are utilized. Besides, an electromagnetic accelerator is prototyped to instantly raise the magnetic field, which accelerates the magnetic micro-robot toward the blocked artery. Blood clots with various lengths (5*10 and 10*10 and 20*10mm^3(Dimeter*length)) are formed inside the tube. The effect of voltage from 100 to 400 volts on destroying different lengths of clot has been studied.

Results: The microrobot enables to destroy the clot and reopen the vessel in a fraction of a second. By increasing the voltage from 100 to 400 volt, the micro-robot is able to destroy clots with longer lengths from 5 to 30 mm.

Conclusion: results confirm that accelerated microbes have a unique potential in piercing clots to reestablish blood flow.

Keywords: Ferromagnetic microrobot, accelerators, thrombose, artery blockage, magnetic field

Introduction:

Obstruction of blood vessels by blood clot or fat can deprive tissue of blood [1]. Without blood, tissue loses oxygen and dies [2]. Fatal diseases such as heart attack and stroke are the result of blocked arteries[3]. While in case of heart attack a thrombus or a fatty deposit blocks an artery supplying blood to the heart leading the death [4], in case of blood vessels in the brain can cause a stroke and paralysis of a part of the body[5], even blocking an artery in the legs leads to deep vein thrombosis[6]. After an obstruction such as heart attack, a quick treatment is strongly requiring to reopen the blocked artery to save the patient's lives[7]. In case of cardiac arrest, a sudden loss of blood flow resulting from the failure of the heart to pump blood, strikes so fast that there's little time to reopen the vein[8]. In fact, the rapid removal of obstruction (less than 6 minutes) in a vein is a critical parameter[9]. This is a serious challenge that requires immediate medical attention.

While approaches such as electric shock are used to treat myocardial infarction[10] , there is no rapid techniques for heart attack and vascular occlusion[11], even in a hospital setting[12]. Meanwhile, in other cases of vascular obstruction such as deep vein thrombosis, there is no rapid treatment[13].

The current conventional methods do not have the potential to remove the blockage quickly inherently[14]. Drug therapy, which involves injecting a drug directly into a blocked artery to break up or dissolve blood clots or fat is not effective because time window for initiating chemical reaction is one of the strictest limitations [15]. Using techniques such as atherectomy, in addition to their inherent limitations, it needs a long time for preparation and involves a time-consuming process that makes it not suitable for emergency cases such as cardiac arrest [16].

However, new technologies such as nano/micro robot can be promising to overcome biomedical engineering challenges .Researchers show that nano/micro robot has a potential to removal fatty deposits from the internal walls of blood vessels [17]. The conventional mechanism of micro robots to remove clogged arteries is that they swim in arteries to reach to obstruction site, then destroy the clogged by acting like a drill and restoring normal blood flow[17]. Chemical and magnetic actuation mechanism are usual actuation methods that is employed to propel the micro robot[18], however, magnetically moving robots are faster and more controllable[19]. micro magnetic particles around 1 micron steer in into the brains of mice based on an open-loop control approach [20]. There are various magnetic actuation methods such as rotating fields, oscillating fields, or field gradients to propel micro robots [18]. However generating high gradient fields to steer the nanoparticles is one of the main challenges [21]. Despite the early success of microrobots, they are unable to move quickly to remove obstructions. Therefore, it is necessary to introduce a new mechanism for the fast movement of microrobots to destroy the obstruction in vessel rapidly.

The principle of accelerated micro-robot

In this section, the technique of accelerating accelerated micro robots under instance magnetic field for eliminating vascular obstruction is described as shown in Figure 1. This technique is based on the rapid movement of a microrobot towards a clogged vessel under a strong magnetic field. A metal micro-robot is injected into a vein near the clot site. Then a magnetic accelerator accelerates the microrobot in a fraction toward the artery blockage to hit it. Due to the high speed of the microrobot (high kinetic energy), clogged in artery will be destroyed or a hole will be created in the artery. The mechanism uses an instant strong magnetic field to accelerate ferromagnetic micro robot to hit the clot and break it down. The electric current is switched from a fast capacitor banks (discharge storage device) into a coil of wire wrapped around a barrel to produce the strong magnetic field required for the rapid acceleration of the metallic micro robots. The force applied to the micro robot is proportional to the current flowing through the coil. the microrobot moves towards the vascular to hit the clot target and pierce it. These systems are very quiet when a micro robot is accelerated at high velocities, are clean, and require little equipment. A magnetic field at the end of the path can stop the micro-robot from moving at the desired point to remove it.

The aim of this study is to evaluate the potential of a novel microrobot that moves at high speed and destroys the clot which is clogged the vessel in-vitro condition. A magnetic accelerator increases the speed of the microrobot in a fraction of a second to reach to sufficient amount to destroy the clot. The effect of important accelerator parameters such as voltage and current in the in the failure of the clot has been studied.

Materials and methods:

Magnetic accelerator and micro robot:

Electromagnetic accelerator consists of one or more coils arranged along the artificial vessels (the coil and artificial vessels are arranged on a same axis), so the path of the accelerating micro robot lies along the central axis of the coils as shown in Figure 2A. The circuit is a boost converter, using 680uF capacitor, with a 12V input and the output capacitor is a 400V, so it can store 40J of energy. The inductance of the coil was 20uH based on 680uF capacitor and 600V max voltage. Power supply 12V power supply was needed for the boost circuit as shown in Figure 2B.

Experimental setting:

An artificial vessel and a transparent polymer tube with diameter of 10 mm were used as the vessel. Human blood was acquired from healthy students between 18 to 25 years old who were healthy according to the Helal Ahmar Ethics Committee (students who voluntarily participate in human subject research after giving informed consent to be the subject of the research). Informed consents were provided by the volunteers. The clots were produced by reaction of 1 ml blood with 200 µl of 0.2 mol/L $CaCl_2$. Blood clots with various lengths (5*10 and 10*10 and 20*10mm^3 (dimeter*length)) are formed inside the tube. Microrobot is a sphere with a diameter of 1 mm made of steel. The effect of voltage from 100 to 400 volts on destroying different lengths of clot has been studied. Each experiment was repeated 3 times.

Results:

The experimental results show that the magnetic accelerator shoots the microrobot towards the clot. As a result of the high speed of the microrobot, the clot is destroyed as shown in Figure 3A. The MRI images of blood clot in different stage of process confirms the perforation of the clot as shown in Figure 3B. There is a direct relationship between voltage and the amount of perforation in the clot as shown on Figure 4. While at 200 volts the microrobot can puncture a 2 cm long clot, by increasing the voltage to 400 volts the clot can pass through a 4 cm long clot. The accelerated micro-robot can pass through a 2 cm long clot at 200 volts, while it can pass through a 3 cm long clot at 400 volts. Meanwhile, efficiency of the micro-robot in reopening the fluid stream (destruction of the small clot (5*10 mm^3 (dimeter*length))) at different voltages (100, 200, 400 and 600 V) is studied as shown in Figure 6. A similar study was performed for medium (10*10 mm$^{3)}$ and large (20*10 mm$^{3)}$ clots at the same voltages as shown in Figure 7 and 8.

Discussion:

Experimental results show that accelerated microrobots have the ability to destroy clots and open the flow of fluid in the artery. The feasibility of accelerated micro robot for removing blood clot and reopening the fluid flow on the vessel can be seen clearly. Figure 4 shows the clot before and after the accelerated microrobot. As shown in the figure, the microrobot is able to perforate the clot and open the fluid flow path. The micro-robot is stopped by a magnetic field (permanent magnet) at the end of the path from inside the transparent polymer tube. The experimental results show that there is a direct relationship between the amount of energy storage in capacitors and the penetration of microrobots inside the clot. In addition, increasing the voltage also causes the microrobot to break up larger clots

In accelerated micro robot, capacitors prepare a large current flowing through the coil of wire and a strong magnetic field forms in a fraction of a second. Therefore, the electrical current flow produces an axial magnetic field inside the coil with maximum value (proportional to current intensity and coil turns number) in the coil central zone [22]. Creating an instantaneous magnetic field leads to accelerating a ferromagnetic microrobots with high velocity toward the clot. Accelerated micro robot hit the clot and destroy it and reopen the fluid flow.

There are several factors govern in this process. In fact, based on physics law, the electrical energy in the capacitor is converted into kinetic energy in the microrobot as follow[23]:

$$KC \square KE \tag{1}$$

KC is conservation of energy and KE is kinetic energy.
Energy stored in a capacitor is found in the following equation 2[24]:

$$KC = \frac{CV^2}{2} \tag{2}$$

According to the conservation of energy equation 3[25]:

$$KE = \frac{1}{2}\frac{m * v^2}{} \tag{3}$$

using Equations 1 and 2, the microrobot speed can theoretically be expressed as follows:

$$v = \sqrt{\frac{CV^2}{m}} \tag{4}$$

Using dynamics equations of motion (equation 5), the microrobot acceleration can be expressed as follows[26]:

$$v_1^2 - v_0^2 = 2al \tag{5}$$

So:

$$a = \frac{v_1^2}{2l} = \frac{\mathrm{CV}^2}{2\mathrm{lm}} \tag{6}$$

Based on Newton's law[25]:

$$F = ma = \frac{\mathrm{CV}^2}{2l} \tag{7}$$

According to Equation 1, there is a direct relationship between the microrobot acceleration and the voltage and capacitance of the capacitor. Figure 5 shows the theoretical relationship between voltage and capacitor and the force applied to the microrobot.

Theoretically, by increasing the amount of energy stored in the capacitors, the acceleration of the microrobot increases, which leads to an increase in the applied force to the microrobot, the microrobot penetrates more into the clot. Experimental results (Figure 3) also confirm that by increasing the amount of energy stored in the capacitors, the microrobot can perforate more longer into the clot.

Figure 6 shows, in case of small clot, that although at low voltage (100 volts), the reopening efficiency of the fluid flow is about 40%, by increasing the voltage to 400 and 600 volts, the clot is completely destroyed and the path reopens completely with high efficiency. Similar tests have been performed for medium and large clots (Figure 7 and 8). The results show that with increasing voltage, the efficiency of opening the fluid path increases and the probability of destroying the clot increases. In fact, as the voltage rises, the accelerating micro-robot strikes the clot with more acceleration and more force, which destroys it and eventually opens the way. In fact, as the voltage rises, the accelerating micro-robot hits the clot with higher acceleration and therefore exerts more force on the clot, which destroys the clot and reopen the flow path. In fact, with increasing voltage, the chances of clot destruction increase.

To treat a heart attack and resuscitate a patient, the bloodstream must be restored very quickly so there is very little time available to the medical team [4] and innovative and rapid methods need to be developed. One of the main challenges of micro-robots is lack of enough speed and energy to eliminate blockages rapidly. To give acceleration to nanoparticles or nano-microbodies requires a strong magnetic field. As mention above, using high magnetic field has two challenges of biological restriction (hazards for vital tissue) [27] and technical restriction of using electromagnet (producing heat, huge size, expensive…)[28]. However, creating strong magnetic field in a fraction of a second will not a harmful effect on the tissues or its deleterious effects will be minimized. It should be mentioned that exposure to a strong magnetic field for a long time can damage the limb[29]. In addition, creating such a strong magnetic field requires large electromagnets and a high current of electricity, which may not be possible in an emergency case[30]. To avoid these two challenges, a magnetic accelerator is designed and prototyped to generate a high-intensity magnetic field in a fraction of a second using low current. Therefore, a portable magnetic accelerator that works with batteries is designed and prototyped to be able to move for emergencies.
The presented accelerated micro robot can be used as a starting point for more advanced experimentation in cardiovascular disease. Although it is at early stage of development, it has the potential to apply in biomedical issue especially for vascular occlusion and heart attack.

Conclusion:
The results showed that the accelerated micro robot has a unique potential to break down blood clots in fraction of a second. There is direct relationship between the voltage of magnetic accelerator and the length of destroyed blood clot. Meanwhile,

by increasing the energy storage in magnetic accelerator capacitors, the microrobot can perforate larger clots.

Ethical approval

- All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.
- This study was approved by the Nursing Committee for Biological Ethics and Biomedical Research at the Islamic Azad University of Shirvan on November 7, 2019, No. T1179315.
- The author gives his consent for publishing all subjects of the paper.
- All participants give their consent for publishing all subjects of the paper.
- This paper is based on the currently accepted ethical principles that apply to research involving humans.

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Figures

Figure 1: The schematic of an accelerated microrobot in removing vascular. (A) Microrobot before acceleration towards vessel occlusion (coil has no electric current). (B) Microrobot after acceleration towards vessel .The electric current in the

coil creates a magnetic field and the micro-robot accelerates towards the clot and destroys the clot, and the micro-robot is eventually stopped by a magnet.

Figure 2: (A) Accelerator electrical circuit diagram. (B) Portable prototype accelerator to accelerate micro-robots.

Figure 3: (A) The image of destroying blood clot by accelerated microrobot, (I) A sample of blood clot in transparent tube (II) blood clot before process, (III) blood clot after process. (B) The MRI image of destroying blood clot by accelerated microrobot, (I) blood clot before process, (II) blood clot after process.

Figure 4: The relationship between voltage and the length of penetrating microrobot into the clot.

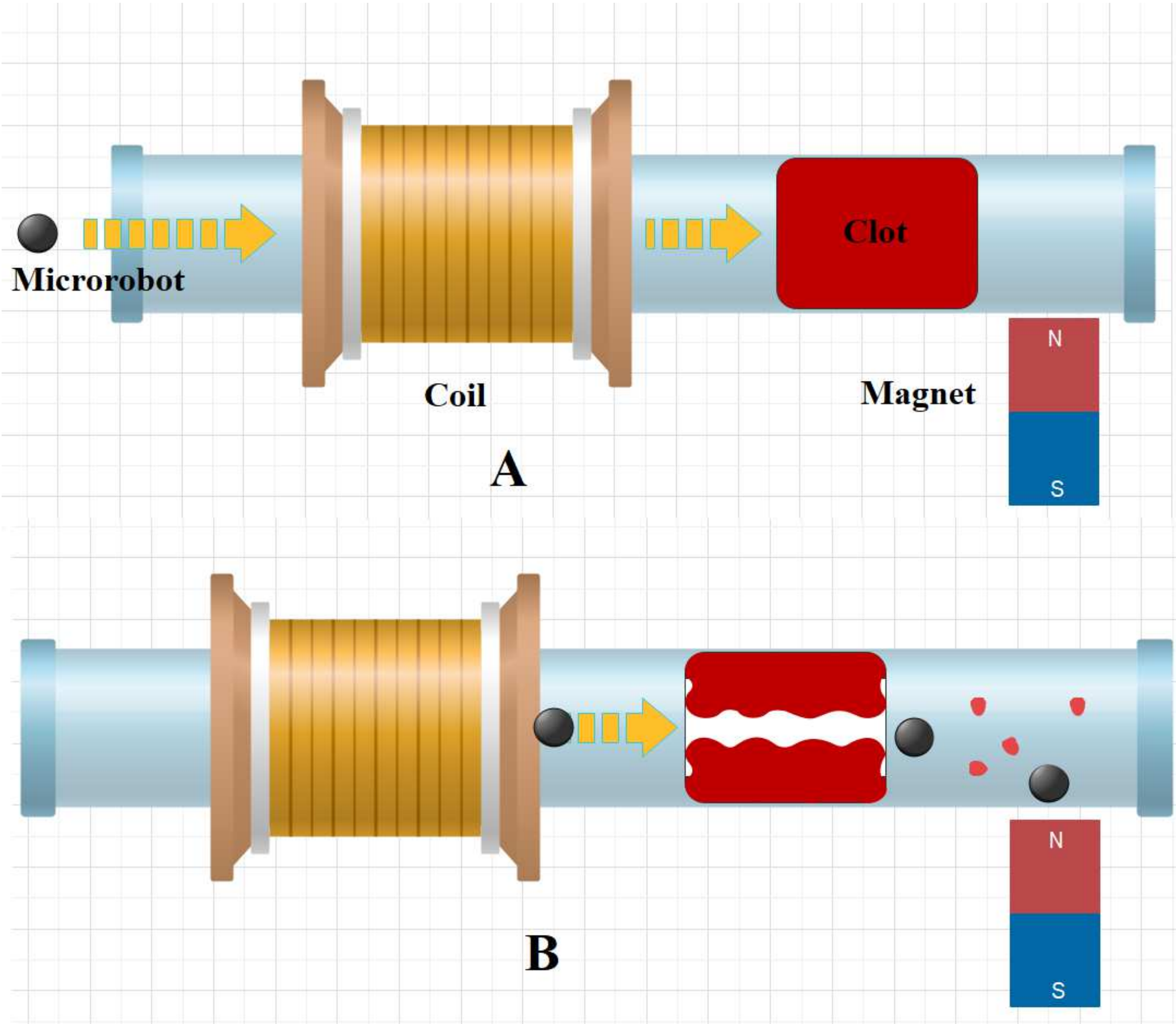
Figure 5: Theoretical relationship between voltage and capacitor and the force applied to the microrobot.

Figure 6: Efficiency of the micro-robot in opening the fluid stream (destruction of the clot (5*10 mm^3 (dimeter*length))) at a voltage of 200, 400 and 600 volts.

Figure 7: Efficiency of the micro-robot in opening the fluid stream (destruction of the clot (10*10 mm^3 (dimeter*length))) at a voltage of 200, 400 and 600 volts.

Figure 8: Efficiency of the micro-robot in opening the fluid stream (destruction of the clot (20*10mm^3 (dimeter*length))) at a voltage of 200, 400 and 600 volts.

Figures



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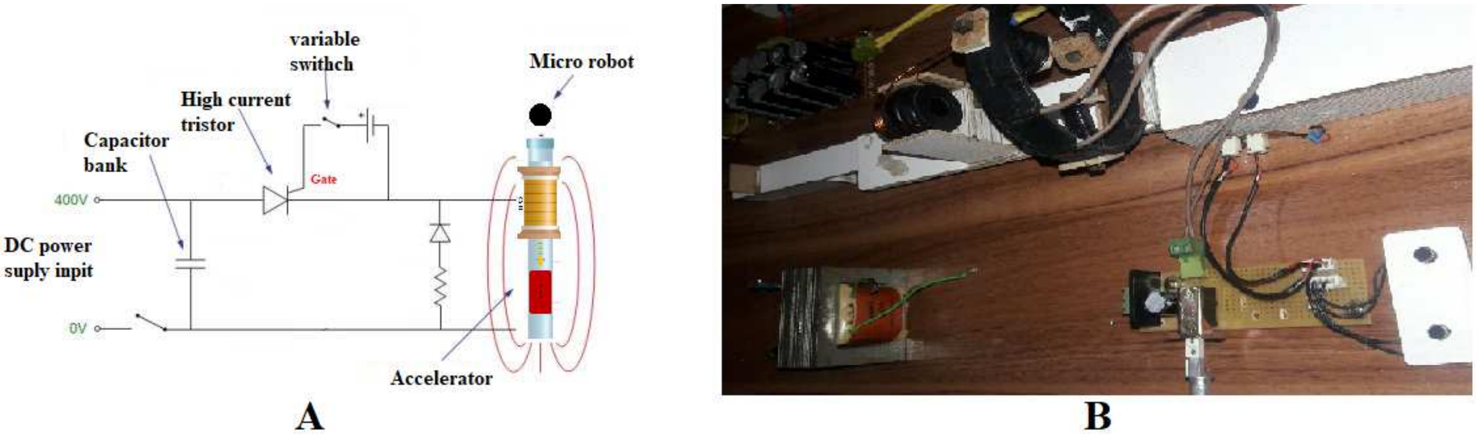

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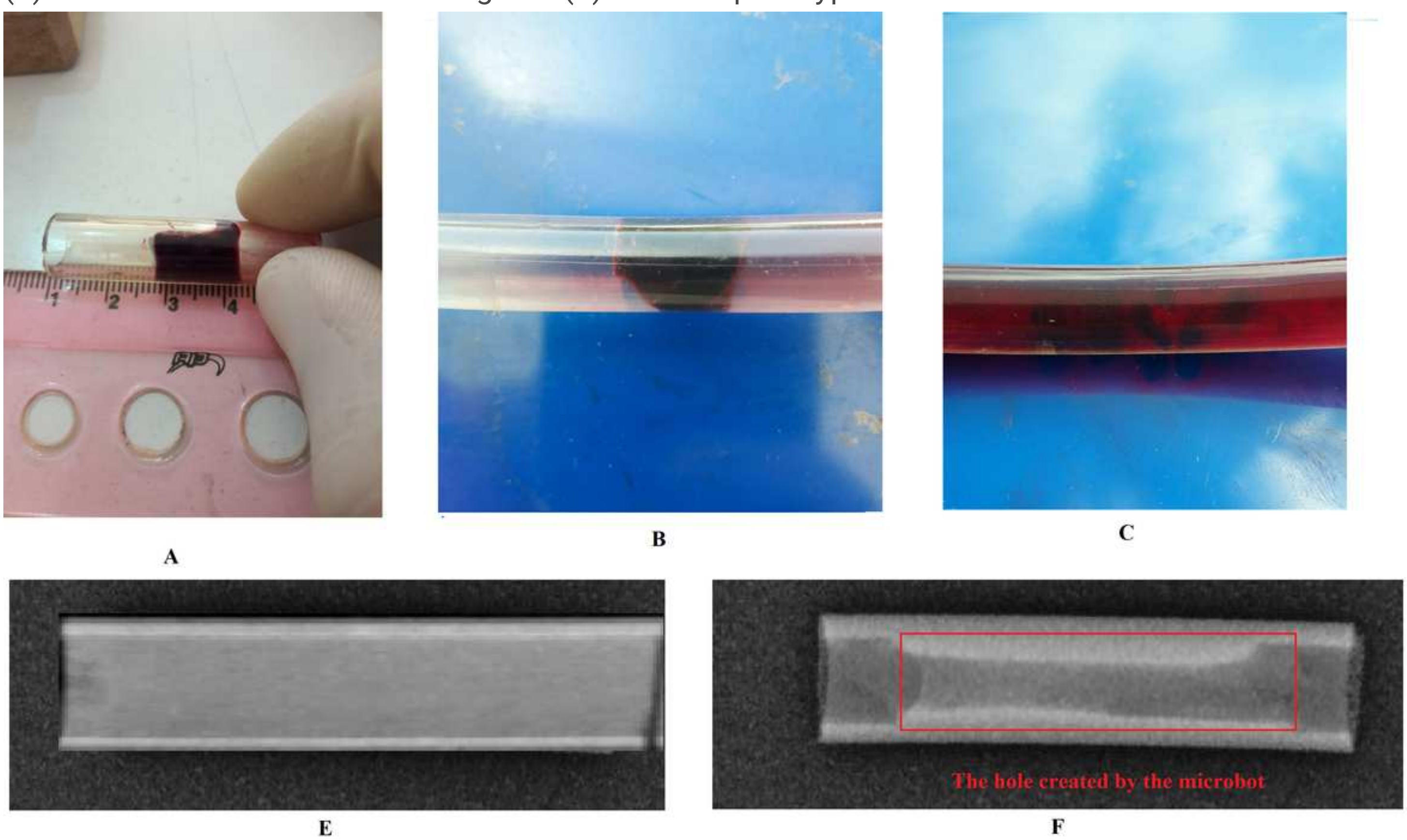

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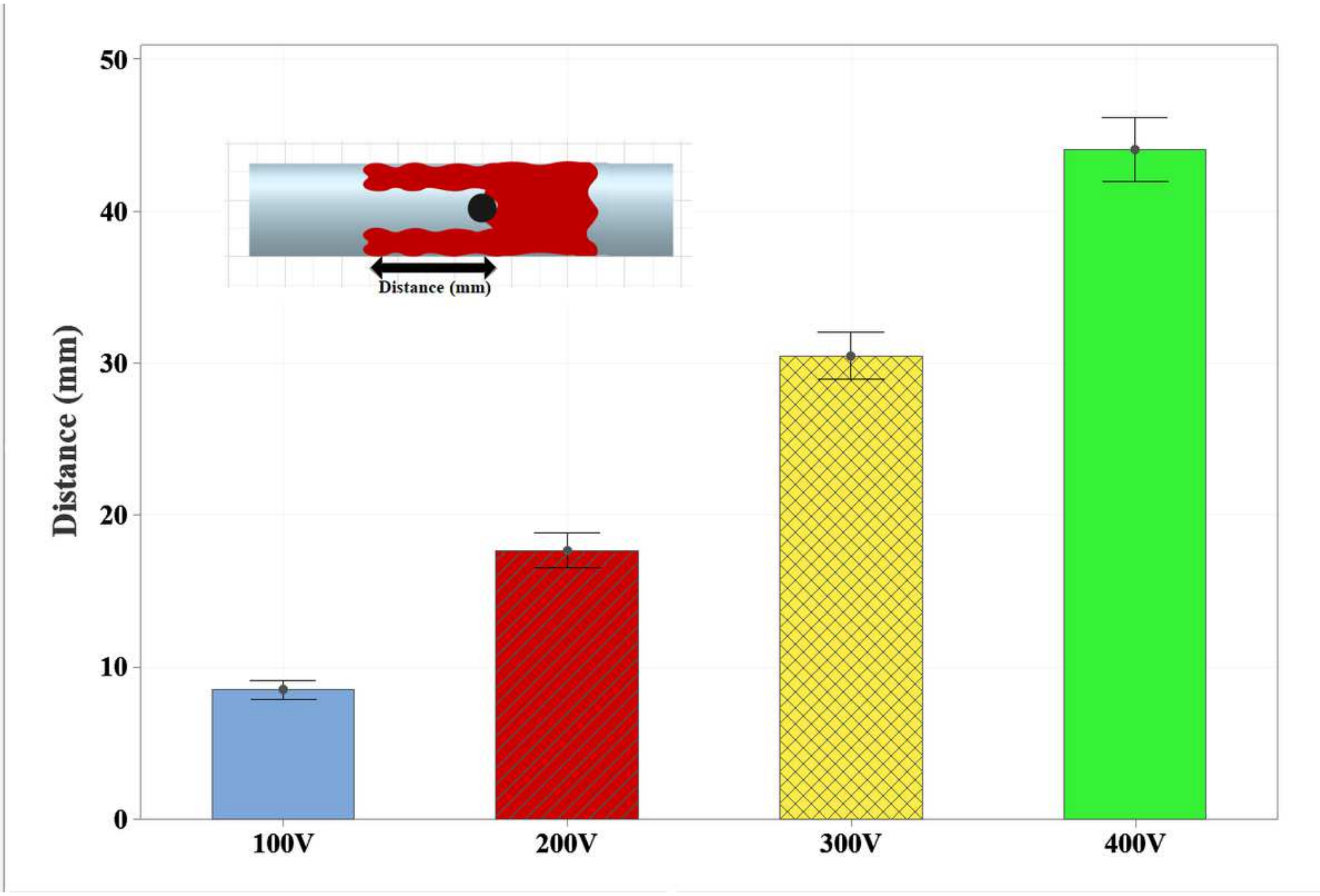

Figure 4

The relationship between voltage and the length of penetrating microrobot into the clot.

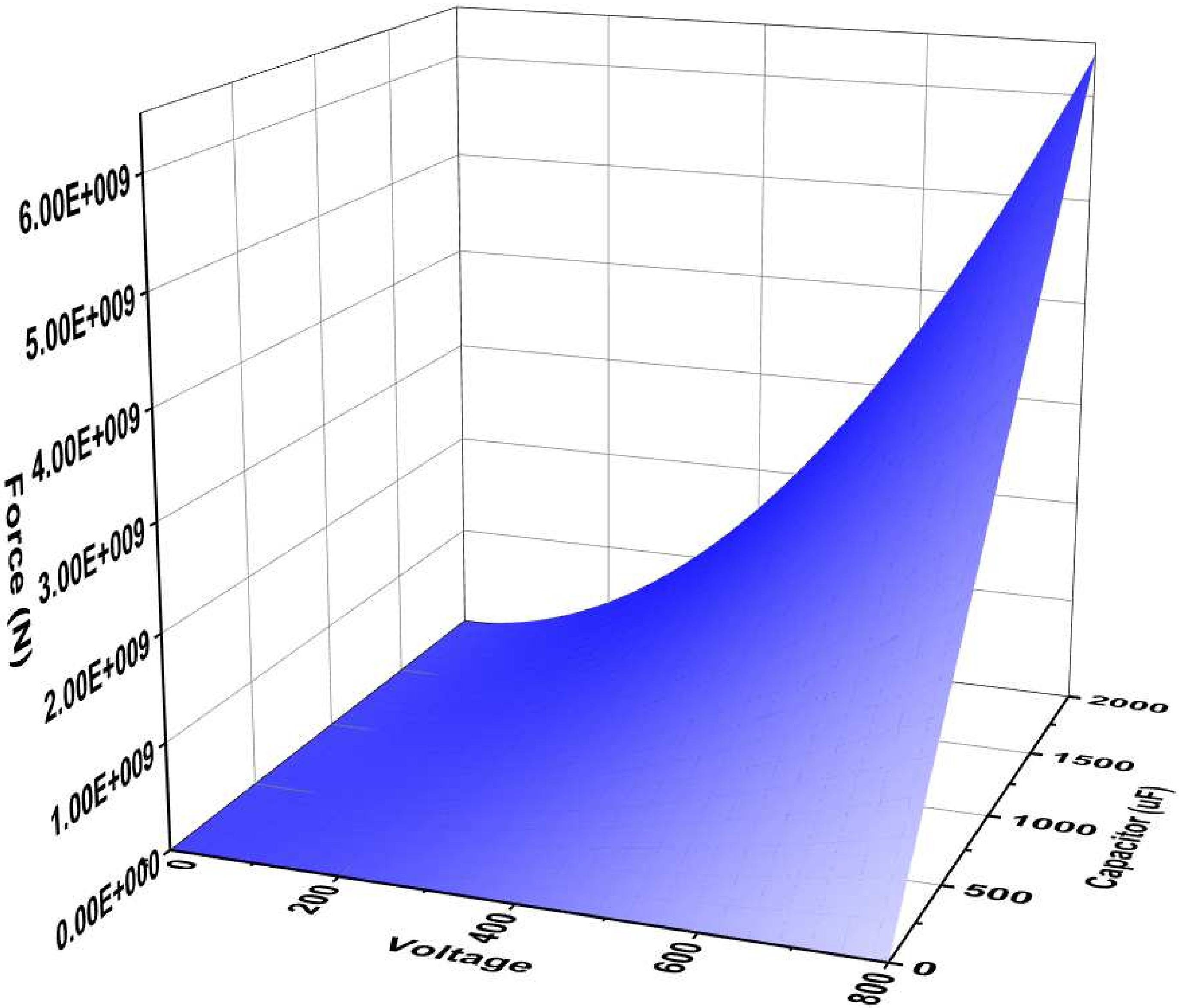

Figure 5

Theoretical relationship between voltage and capacitor and the force applied to the microrobot.

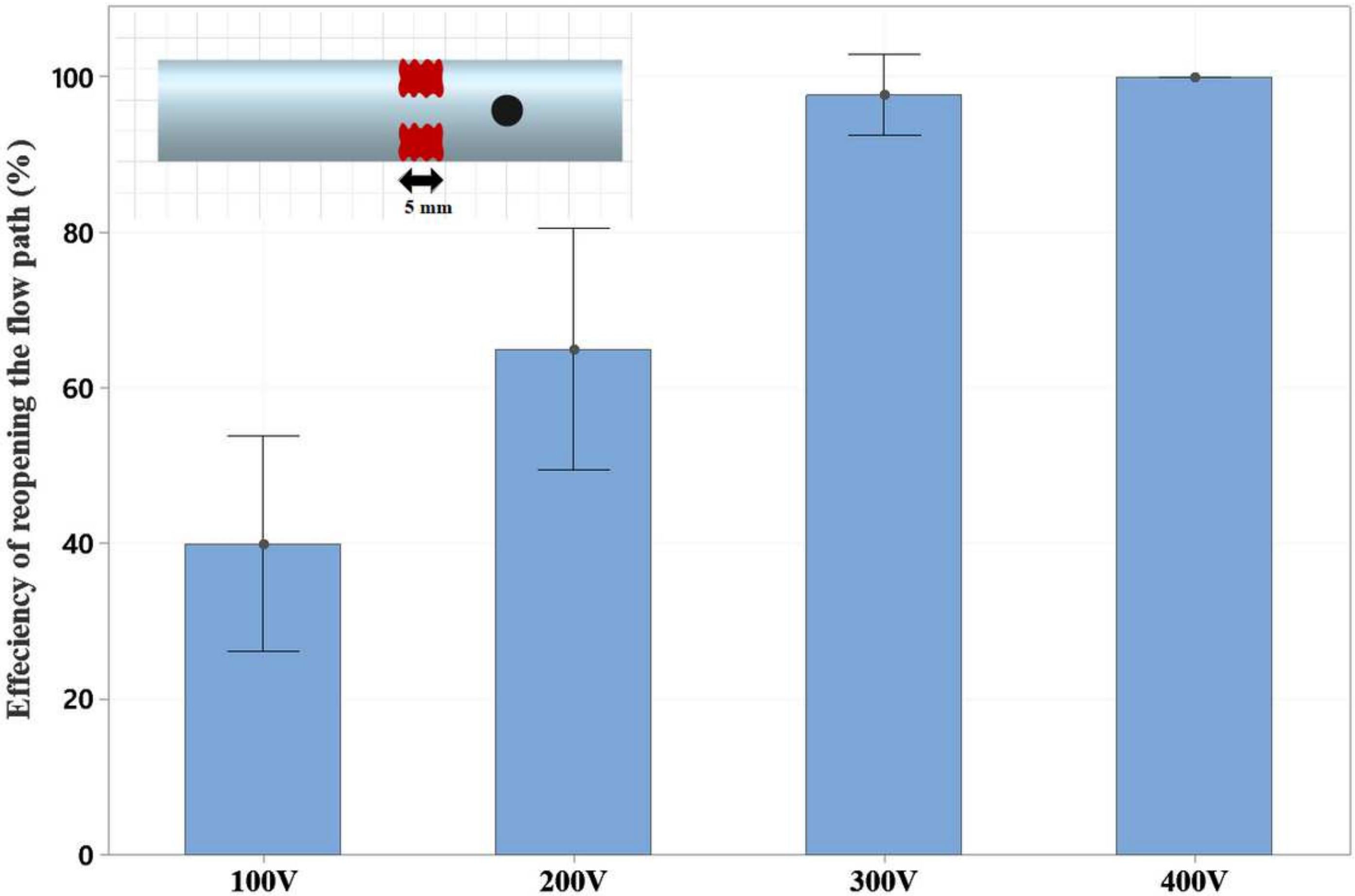

Figure 6

Efficiency of the micro-robot in opening the fluid stream (destruction of the clot (5*10 mm3 (dimeter*length))) at a voltage of 200, 400 and 600 volts.

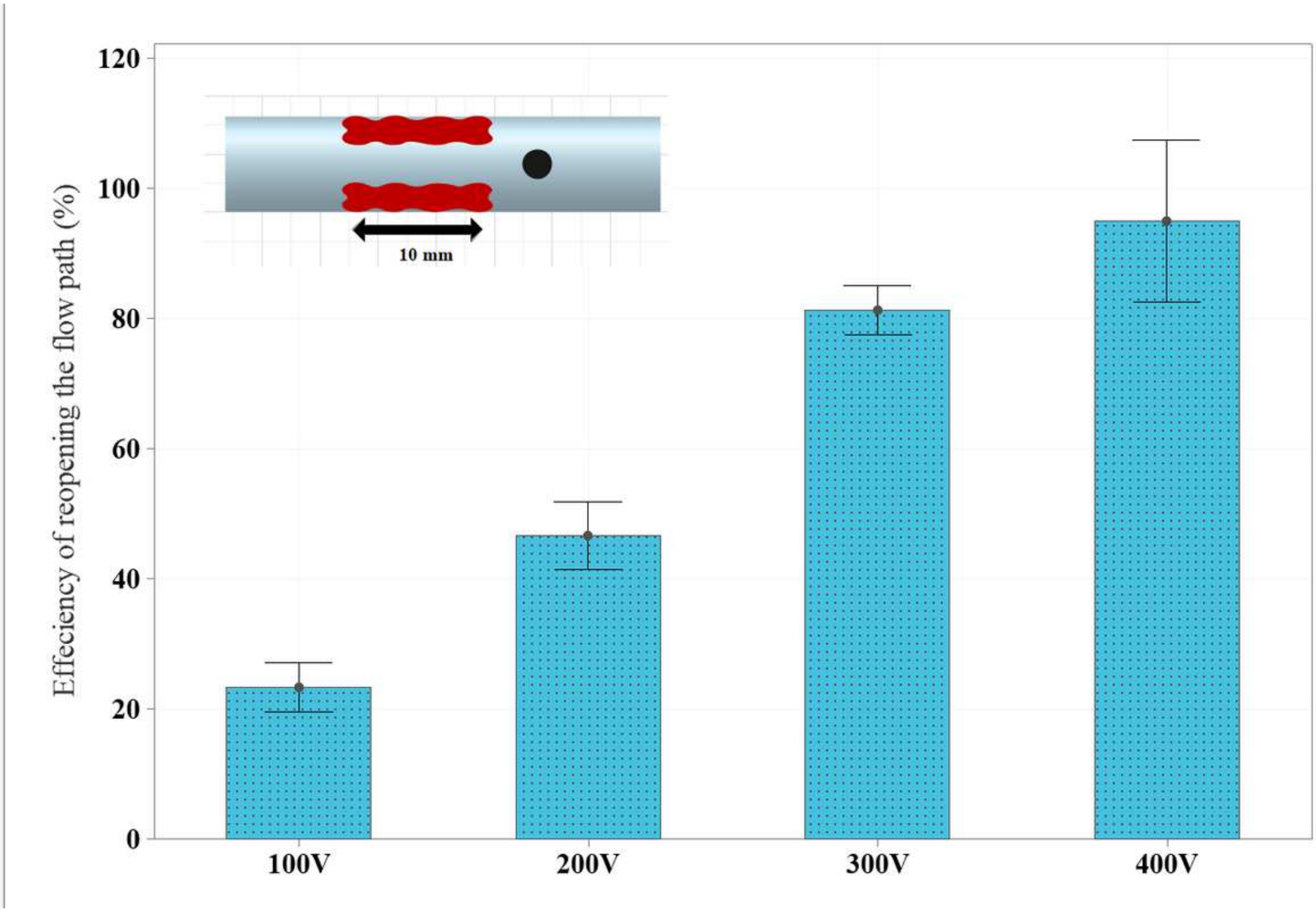

Figure 7

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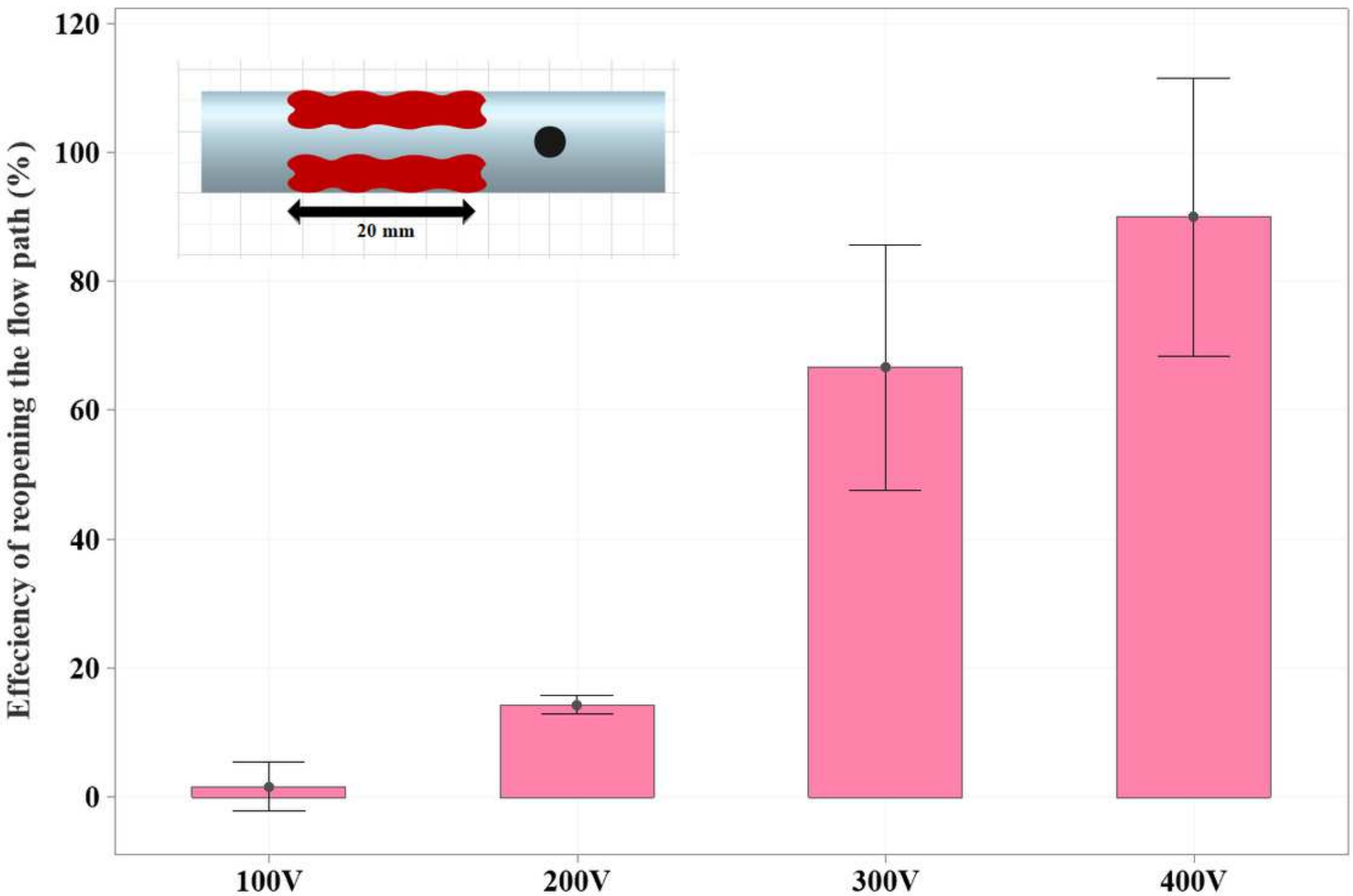

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