Helical Structures for Medical Applications

M Eldeeb1, H Mattar2, H Hatem1, D Elmahdy2, N Shanan3, M Elwi2, A Klingner4, A Ramzy2*

1 Mechatronics Engineering Department, Faculty of Engineering and Materials Science, German University in Cairo, New Cairo 11835, Egypt.
2 Materials Engineering Department, Faculty of Engineering and Materials Science, German University in Cairo, New Cairo 11835, Egypt.
3 Department of Pharmacology and Toxicology, Faculty of Pharmacy and Biotechnology, German University in Cairo, Egypt.
4 Physics Department, Faculty of Engineering and Materials Science, German University in Cairo, New Cairo 11835, Egypt.
* Email:amna.ramzy@guc.edu.eg

Abstract. The latest advances in the field of microrobotics assisted medical experts in the treatment of some of human diseases especially intravascular diseases such as atherosclerosis. In this research, a phantom for the atherosclerotic plaque material is fabricated using Gelatine and Nano Hydroxyapatite in a catheter tube to mimic the condition in the human body in vitro. For plaque penetration a helical microrobot is designed to achieve the optimum plaque clearing efficiency. The robot is a remotely controlled micro helical magnetic based metallic robot which is inserted in the catheter to penetrate the phantom by rotational motion along its axis. The motion of the robot during mechanical grinding of the plaque phantom is simulated using MATLAB where the distance of the robot’s journey inside the plaque phantom is plotted against the time consumed by the robot.

1. Introduction

Atherosclerosis is a disease in which plaque is created inside the arteries. Plaque consists of cholesterol, fats, calcium, and other substances that are deposited on the walls of the arteries. As time passes, the plaque becomes harder and accordingly the arteries become narrower. This decreases the flow of oxygen-rich blood all over the human body. Atherosclerosis is capable of causing stroke and heart disease. Cardiovascular diseases (CVDs) are a common cause of death all around the world. In 2016, approximately 17.9 million people died because of CVD, and this represents 31% of worldwide deaths and 85% of these deaths are because of stroke and heart diseases.

In 2005, Hansson, G.K. stated that atherosclerotic lesions (atheromata) consist of lipids, debris, cells, and tissue elements. Another component that forms the plaque is calcium phosphate hydroxyapatite. In 1994, Demer et al. pointed out that in coronary arteries, when the plaque is built up the amount of calcium can be 10 to 80 folds. By using intravascular ultrasound, the calcified plaques are more than 80%. 90% of patients who have coronary artery disease had coronary calcification.

In their research, Lihong Lao et al. studied the arterial plaque composition and simulated its behaviour by selective mineralization of hydrogel lumens to be able to perform ex-vivo experiments. Using polyacrylamide, the synthetic lumens were moulded by casting the acrylamide solutions into a transparent cylindrical mould to mimic the arterial plaque. Another research that focused on the hard part of the plaque was concerned with how to tackle and remove the plaque using rotational ablation. In their model, a mixture of Hydroxyapatite and Polylactic acid was used and its resemblance to the calcified plaque was confirmed using Nano indentation.
In 2018, Lee, S. et al. built up Magnetic Drilling Actuators, that were made of Ni and cobalt (Co) and were covered with titanium (Ti) or titanium oxide (TiO$_2$) for the microrobots to be biocompatible. To improve the performance of the drilling and overcome the torque and force of gravity, they used Nd permanent magnet.[7]

In 2010, Park, S. et al. noted that robots can be helpful in coronary interventions. They are willing to make a microrobot that should be able to move freely and recognize the target location which would serve as both an effective drilling tool and a thrombus collector.[8]

In this research paper, a phantom of the arterial plaque was fabricated inside a catheter tube using gelatin and hydroxyapatite. A magnetically controlled helical micro-robot was then introduced to the catheter and the penetration of the robot inside the plaque phantom was studied.

2. Materials and Methods

The experiments are divided into three main stages as follows;

2.1 Stage 1: Plaque Phantom Fabrication

Three mixtures of Gelatine/Hydroxyapatite (HA) were prepared in the following compositions: 5wt%, 10wt% and 15wt% solute in solvent (boiled distilled water); with a ratio of 60:40 HA to Gelatin.

The Gelatin was mixed with HA in boiled distilled water using a magnetic stirrer at 600±5 rpm for 15 minutes. The mixture is then inserted in a catheter tube of diameter 5 mm and plugged from both ends then left to cure for 1 hour at 5°C.

2.2 Stage II: Fabrication of Helical Microrobot

The helical microrobot is made of a copper wire of diameter 0.3 mm that is wound in a spring form with a pitch of 1.3 mm, a total length of 5 mm and a diameter of 1 mm. A 1 mm diameter permanent magnet supplied by Supermagnete, Gottmadingen, Germany is mounted on the robot as shown in figure 1 to provide the required magnetic properties. The magnet is mounted so that the magnetic moment of the head is perpendicular to the axis of the robot.

![Figure 1. Helical microrobot.](image)

Figure 1. Helical microrobot.

![Figure 2. Helical microrobot by solidworks.](image)

Figure 2. Helical microrobot by solidworks.

2.3 Stage III: Plaque penetration by helical microrobot
The penetration experiment takes place inside a special set-up called HeliMag shown in figure 3. The helical microrobot is steered and propelled under the effect of the magnetic fields. The magnetic fields are generated by two rotating permanent magnets. An Arduino control board is used to control and synchronize their motion. To minimize vibrations, the system is put on tuned damped upgradable smart table.

\[ T_m = m \times B, \]

where \( m \) and \( B \) are the magnetic moment and magnetic field, respectively. When the robot swims in liquid medium (water), the frictional torque \( T_f = 0 \), therefore, the drag torque \( T_d = T_m \). From the equation of drag torque, the speed of the robot was measured. \[ U, \Omega \]

\[ \left( \begin{array}{c} T_x \\ T_y \\ T_z \end{array} \right) = \left( \begin{array}{ccc} A_{11} & A_{12} \\ A_{12} & A_{22} \end{array} \right) \left( \begin{array}{c} U \\ \Omega \end{array} \right), \]

where \( U, \Omega \) are the linear and angular velocity of the robot, and the parameters of the matrix are:

\[ A_{11} = 2\pi nr \left( \frac{\zeta_{\parallel} \cos^2 \theta + \zeta_{\perp} \sin^2 \theta}{\sin \theta} \right), \]

\[ A_{12} = 2\pi nr^2 (\zeta_{\parallel} - \zeta_{\perp}) \cos \theta, \]

2.4 Stage IV: Speed of the Robot & Rubbing Simulation

By using modelling equations, the speed of the helical robot and the size of the part removed from the plaque were calculated and then the penetration process was simulated and visualized using MATLAB. The plaque mass was modelled as a cylindrical shape of diameter 4 mm and length 4.5 mm.

First, the magnetic torque which is exerted on the robot was calculated by using

\[ T_m = m \times B, \]

where \( m \) and \( B \) are the magnetic moment and magnetic field, respectively. When the robot swims in liquid medium (water), the frictional torque \( T_f = 0 \), therefore, the drag torque \( T_d = T_m \). From the equation of drag torque, the speed of the robot was measured. \[ U, \Omega \]

\[ \left( \begin{array}{c} T_x \\ T_y \\ T_z \end{array} \right) = \left( \begin{array}{ccc} A_{11} & A_{12} \\ A_{12} & A_{22} \end{array} \right) \left( \begin{array}{c} U \\ \Omega \end{array} \right), \]
Where \( n, r \) are the number of turns and radii of the helix, and \( \zeta, \zeta_\perp \) are the parallel and normal viscous drag coefficients.

\[
\zeta = \frac{4\pi \eta}{\ln\left(\frac{0.36\pi}{b \sin\theta}\right) + 0.5},
\]

(6)

\[
\zeta_\perp = \frac{2\pi \eta}{\ln\left(\frac{0.36\pi}{b \sin\theta}\right)},
\]

(7)

Where \( \eta \) is the fluid viscosity and \( b \) is the radii of tail. [9]

If the robot touches the plaque and does fritting, then its speed \( \approx 0 \) and \( T_d = A22^*\omega \). Therefore, the size of the removing part from the plaque(\( \delta_{bc} \)) is calculated using [10]

\[
\delta_{bc} = \min\left(\sqrt{\frac{2\sqrt{|m| - |d|}}{\pi r^2}}, 0.5b\right),
\]

(8)

3. Results and Analysis

The discussion of this research will be divided into two parts the first part is the experimental part where the plaque phantom penetration with the helical robot is presented. The second part is the simulation part where the speed and motion of the helical microrobot during rubbing inside the plaque will be visualized and discussed in comparison to the experimental results.

3.1 Plaque phantom penetration

The fabricated plaque is put inside the catheter tube produced. The plaque has a white high viscosity mass as shown in figure 6.

![Plaque Phantom inside the catheter tube: Left: side view, Right: cross section.](image)

By visual and physical inspection (applying pressure by the finger), the 5wt% plaque sample was soft yet holding its own shape and not flowing: elastic yet easily penetrated with small pressure. The 10wt% sample was harder than the 5wt% sample and even more elastic yet it was penetrated with enough pressure. The 15wt% sample was the hardest of them all resembling a soft rubbery texture and was the most elastic and could only be penetrated with the use of excessive force.
In the sample with 5wt% composition, the helical microrobot could easily cover an average distance of 0.191 cm in one second whereas by increasing the wt% of HA, the rigidity of the phantom plaque mass increased causing more resistance on the robot and consequently it covered a smaller distance (0.118 cm) in the same time.

A remarkable drop in the velocity of the robot could be noticed by further increasing the amount of HA to 15wt% where the velocity dropped by almost 10 fold from 0.118 to 0.011 cm/s. It can be easily concluded that the harder the plaque phantom is, the slower the penetration velocity of the robot gets. This could be attributed to the presence of high frictional forces between the robot body and the abrasive HA content. This same results was also discussed by Chenghao Bi et al [11] where the authors demonstrated the ability of a magnetic microrobot to travel through wet conditions inside a murine colon. The results showed that when starting in water medium the robot reached a maximum speed of 2.2 mm/s while the speed of the robot inside 1% Tylose solution which resembles the ultrasonic hydrogel decreased to roughly 0.2 mm/s.

The motion of the helical microrobot throughout the whole journey of penetration in the 10wt% sample is detailed in figure 7 (right). From the graph, it can be noticed that the robot doesn’t follow a constant course of motion where the velocity changes stepwise according to the position of the robot inside the plaque mass. During the penetration experiment, it was observed that the robot rotates along its axis to rub and remove a small plaque mass then it proceeds linearly afterwards matching another step on the graph. This nature of rubbing was also simulated by Dai et al [12] where the dynamic motion of a rubbing rotor was simulated and studied. It was found out that the rotor speed was not constant all over its rubbing motion and rather creates a whirl like orbits whose amplitude was directly proportional to the applied frequency level. This varying amplitude occurs due to the rubbing friction and reflects on the stability of the rotational speed of the rotor.

3.2 Rubbing motion simulation

The removing part of plaque $\delta_{bc} = 0.075$mm was determined using equation (8). Then, the translation and rotation of the helical robot while moving in water was simulated. Then, the penetration process of the helical robot against the plaque was visualized.

When the robot first contacts the plaque, it rotates along its axis without linear motion. The rotational motion of the helical robot causes the rubbing and consequently the removal of the plaque at the contact area, this in turn gives the robot a free volume allowing it to move forward and further penetrate into the plaque mass. This process will be done all over again till the robot reaches the end of the tube. In the model, 1 pixel is equals to $\delta_{bc}$ and the total length of the tube is given by 15mm and the diameter 4.5mmAll dimensions were converted to pixel by dividing by $\delta_{bc}$. In figure 8, the cross section of the catheter tube containing the robot is visualized in two different positions; a) water medium, b) plaque medium, c) is the complete side view of the tube showing both phases water (blue) and plaque (orange). The pixeled micro-helical robot is shown in d).
In figure 9(a), the motion of the helical robot in the water medium (blue) is visualized where it can be noticed that the velocity of the robot is constant since there is low resistance exerted by the Newtonian fluid. The graph in figure 9(b) shows the volume of the plaque in mm$^3$ over time in seconds. As the robot is still in the water medium and it does not touch the plaque, the volume of the plaque remains constant. The model succeeds in visualizing the dynamic motion of the robot as the medium changes from water to plaque as shown in figure 9(c) where the velocity of the robot changes in stepwise accompanied by a decrease in the volume of the plaque as illustrated in figure 9(d).
The simulation of the robot behavior was successfully simulated using the model presented in section 2.4. The same dynamic behavior of magnetic microrobots was also discussed by several researchers where Öpöz and Chen [13] used the FEM method to simulate the rubbing behavior of a single grain. The behavior of the grain was found out to pass by three main stages namely: rubbing, ploughing and cutting resembling the elastic deformation, elastic-plastic deformation and cutting zones respectively. The path of grain was simulated over the three stages where the researchers illustrated changes in the grain displacement path and the exerted forces on the grain related to the zone. The simulation results showed that the forces begin at high values (in our microrobot case is the phase where rubbing occurs without linear displacement) and then a subsequent decrease in the forces occurs due to the removal of material (in our case the linear penetration of the robot inside the plaque mass after volume decrease).

The same rubbing behavior was also discussed by Khalil et al. where the drag forces and the torque exerted on the magnetic micro-helical robot was simulated [10]. The results showed that the forces and torques induced during the rubbing action are fluctuating which cause the variation of the robot speed along the penetration path.

4. Conclusion

In this research paper, a plaque phantom was fabricated using a mixture of gelatine and Hydroxyapatite at 5wt%, 10wt% and 15wt% to simulate the behaviour of the helical microrobot during rubbing motion in vitro. The motion of the robot inside the plaque phantom was captured, analysed and the average velocity at each concentration of HA was calculated. A correlation between the concentration of the HA and the robot velocity was deduced where maximum robot velocity was achieved at 5wt% hydroxyapatite. A detailed velocity curve of a selected concentration (10wt%) was then plotted. The rubbing motion behaviour of the helical microrobot was modelled then simulated and visualized using MATLAB.

The detailed velocity curve was then used to verify the simulated robot motion as seen in figure 10. The blue colour resembles water medium where there is no friction or resistance on the robot in the first 20 seconds. Starting second 23 the robot tip contacts the plaque (yellow colour) and friction occurs causing the slope of the curve to change. Full penetration occurs after t=100 s where the speed of the robot increases by exiting the resisting medium.

---

**References**

1. Arteriosclerosis / atherosclerosis Symptoms & causes. Mayo Clinic April 24, 2018 [www.mayoclinic.org/diseases-conditions/arteriosclerosis-atherosclerosis/symptoms-causes/syc-20350569](www.mayoclinic.org/diseases-conditions/arteriosclerosis-atherosclerosis/symptoms-causes/syc-20350569)
2. Cardiovascular diseases (CVDs). World Health Organization May 17, 2017
   www.who.int/en/news-room/fact-sheets/detail/cardiovascular-diseases-(cvds)

3. Hansson G 2005 Inflammation, Atherosclerosis, and Coronary Artery Disease. New
   England Journal of Medicine 352(16), 1685–1695.

4. Demer L, Watson K and Boström K 1994 Mechanism of calcification in
   atherosclerosis Trends in cardiovascular medicine 4(1), 45-49.

5. Lao L, Robinson S, Peele B, Zhao H, Murray B, Min J, Mosadegh B, Dunham S and
   Shepherd R 2017 Selective Mineralization of Tough Hydrogel Lumens for Simulating
   Arterial Plaque. Advanced Engineering Materials 19, 1-8.

6. Kim M, Kim H, Kim N, Yoon H and Ahn S 2011. A rotational ablation tool for
   calcified atherosclerotic plaque removal. Biomedical microdevices 13(6), 963–971.

7. Lee S, Lee S, Kim S, Yoon C, Park H, Kim J and Choi H 2018 Fabrication and
   Characterization of a Magnetic Drilling Actuator for Navigation in a Three-
   dimensional Phantom Vascular Network. Scientific Reports 8(1), 1-9.

8. Park S, Cha K and Park J 2010 Development of Biomedical Microrobot for
   Intravascular Therapy. International Journal of Advanced Robotic Systems 7(1), 91-98.

9. Abbott J, Peyer K, Lagomarsino M, Zhang L, Dong L, Kaliakatsos I and Nelson B
   2009 How Should Microrobots Swim? The International Journal of Robotics
   Research, 28(11-12), 1434–1447.

10. Khalil I, Tabak A, Sadek K, Mahdy D, Hamdi N and Sitti M 2017 Rubbing Against
    Blood Clots Using Helical Robots: Modeling and In Vitro Experimental Validation.
    IEEE Robotics and Automation Letters, 2(2), 927–934.

11. Bi C, Niedert E, Adam G, Lambert E, Solorio L, Goergen C and Cappelleri D 2019
    Tumbling Magnetic Microrobots for Biomedical Applications. 2019 International
    Conference on Manipulation, Automation and Robotics at Small Scales (MARS). (-),
    1-6.

12. Dai X, Jin Z and Zhang X 2002 DYNAMIC BEHAVIOR OF THE FULL
    ROTOR/STOP RUBBING: NUMERICAL SIMULATION AND EXPERIMENTAL
    VERIFICATION. Journal of Sound and Vibration, 251(5), 807–822.

13. Öpöz T and Chen X 2010 An Investigation of the Rubbing and Ploughing in Single
    Grain Grinding using Finite Element Method. In: 8th international Conference on
    Manufacturing Research. (-), 256-261.