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Micro-Needle with Polygonal Structure of Micro-Channel for Stress and Blood or Drug Flow Optimization

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Abstract

This paper presents micro-needle with different tip and inner structure of the needle for optimizations of pain stresses and drug or blood deliveries. The micro-needle comes with several design's parameters of length ranging from 5mm to 50mm and diameter ranging from 100µm to 200µm. A hollow micro-needle with four different tip designs which are 10°, D3-2, D6 and Quadruple are also designed to optimize the pain stresses parameters. In order to improve the flow deliveries, the inner structure of the channel is modified into various polygonal shape which is square, hexagon and dodecagon. It shows that, having less contact surface area between the skin and micro-needle's tip and polygonal shape of inner channel has better performance for both of the objectives. These feasible region of average velocity and stress of the micro-needle have satisfied in determining the best design for tip and inner channel of the micro-needle under certain conditions and constraints. The three-dimensional geometry study had improved the insertions performance and efficiencies in painless drug or blood deliveries.

Keywords*:* Micro-needle, drug delivery, blood delivery, polygonal micro-needle, quadrupletip micro-needle

1. Introduction

Injecting drug and blood withdrawing techniques are obtained either from arteries or veins. By using hypodermic needle to penetrate human skin until reach the arteries or veins is surely uncomfortable and painful. From the beginning of the realization of painless needle from mosquito's mechanism of blood withdrawal, lots of research is done to improve the efficiency of the micro-needles for drug delivery and blood withdrawal from various sizes of needle and designs. Needles are defined as sharp hypodermic needle that has a function to be painless while completing the task of penetrating the human outermost skin to withdraw blood or injecting fluid into the blood stream[1]~[4]. From hypodermic needles to the current conventional micro-needle, the advancement of the researches leads to the technologies of micro-needles in improving the flow and performance while completing the task of penetrating the human outermost skin [5]. This gives better improvement in dynamic characteristics by modifying the geometries of the micro-channel which is inspired by polygonal shape with different dimensions [6]~[7].

Human skin is the largest organ of the human body and one of the complex tissues of the human body which has different functions components and structure [8]. Structure of outermost layer, stratum corneum is very complex and acts as barrier. These methods are used in previous research makes the delivery more successful. Problem encountered when drug is too complex and difficult to be absorbed from the skin to the vessel. This layer is composed of cornified dead cell which is 20-40µm thick [9]. Human skin in each part itself has different in their young modulus and differ in each part of human body as it exhibits the properties of non-homogenous, anisotropic nonlinear and viscoelastic [10]. The level of hydration of human skin also affect the young modulus and level of pain when the needle is about to penetrate the skin [11].

Penetrating human skin with a hypodermic needle is painful and uncomfortable. A low-invasive needle is very much desired in medical field in order to do lot of activities that involve needle. By imitating mosquito fascicle, lots of researcher has put their considerable effort in developing micro-needles in order to replace the normal and traditional hypodermic needle. From hypodermic needle, the advancement of the researches leads to the technologies of micro-needles with the efforts to bypass the stratum corneum that enhance drug penetration which is penetration up to 1.5mm is considered to be painless [12]. Sharper tip of needle ease the penetration process as the generated stress is only little compared to blunt tip. Stratum corneum, which is 10-15µm, the outer layer of skin, gives more advantage to micro-needle compared to the traditional hypodermic needle as the conventional needle that pass this layer of skin does transmit the drugs effectively but there is possibility of infection and pain. While, micro-needles which can be fabricated long

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enough, pass this layer, results in less pain, infection nor injuries [13].

2. Methodology

Fig. 1 shows the micro-needles with inner channel design of circular, square, hexagon, dodecagon respectively. Several micro-needle's tip designs are designed with the parameter of 100µm and 150µm inner-diameter with three different channel length which is 10mm, 25mm and 50mm. The medium for the flow improvement research simulation is blood and drug represented by water. The velocity of the fluid delivery penetrating micro-needle is 0.01m/s. This is the average laminar inflow of non-Newtonian properties.

The materials used in this section is polysilicon and titanium. This selection is based on the differences in surface roughness and history of manufacturing of micro-needle which is having suitable physical properties in biomedical fields. The important factors in choosing the material in biomedical fields are the biocompatibility of the material. The surface roughness of polysilicon is 0.5 while titanium is having surface roughness of 0.1.

This research focuses more on the fluid flow velocity and its energy losses in micro-needles with respect to the design parameters and slip length applied according to micro-needle's length. The physic settings for the simulation is using laminar two-phase flow. The moving meshes as the fluids used in the delivery are multi-phase mixture of fluid.

The energy equation for the energy losses in fluid flow is applied as in Eq. 1.

Energy equation considering energy losses, E_L

$$\frac{V_1^2}{2} + gz + \frac{P_1}{\rho} = \frac{V_1^2}{2} + gz + \frac{P_2}{\rho} + E_L \quad (1)$$

Equation of continuity,

$$A_1 V_1 = A_2 V_2$$

$$V_2 = \frac{A_1}{A_2} V_1$$

Substitute value of V_2, we get

$$E_L = \frac{P_1 - P_2}{\rho} + \frac{V_1^2}{2} - \frac{\frac{A_1^2}{A_2^2} V_1^2}{2}$$

$$E_L = \frac{P_1 - P_2}{\rho} + \frac{V_1^2}{2}\left(1 - \frac{A_2^2}{A_2^2}\right) \quad (2)$$

The area of the channel remained the same along the micro-needle. The final equation that we obtained is as the following and applied to find the energy losses for the fluid flow.

$$E_L = \frac{P_1 - P_2}{\rho} \quad (3)$$

Fig. 2 shows the 10°, D3-2, D6 and quadrupletip micro-needle which are used for the stress simulation optimization. Micro-needles designed are a hollow cylinder with dimension of 300µm as the outer diameter and 180µm as the inner diameter. Penetrating human skin, the simulation of the maximum stress on human skin resulted by penetrating micro-needles by 0.5mm downward was done by imitating mosquito proboscis when penetrating human skin for blood sucking purpose.

The micro-needles are penetrating the rubber perpendicularly to the rubber surface in order to find the maximum value of the parameters mention above. However, it is best if the piercing angle of the micro-needles is in 45° to the rubber surface; as this is claim to be the best angle to withdraw the human blood efficiently [14]. The micro-needles are set to fix and rigid mode. They are also set to be the reference geometry by -0.5mm at y-axis.

3. Results and Discussions

The velocity simulation result of circular, square, hexagon and dodecagon for drug delivery is sorted from the highest velocity simulated for each material, length and diameter. From these 96 sets of microneedles, the chosen microneedles based on performance is tabulated in Table. 1. The table shows that using square shape, polysilicon, 0.15mm diameter and 50mm length produced the highest velocity. The velocity simulation result from circular, square, hexagon and dodecagon for blood delivery is sorted from the highest velocity simulated for each material, length and diameter. Based on Table. 2, it shows that using hexagon shape, titanium, 0.10 diameter and 50mm length produced the highest velocity. The overall performances of the micro-needles are summarized in Fig. 3.

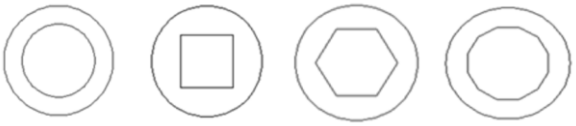

Fig. 1 Micro-needle channel inner designs

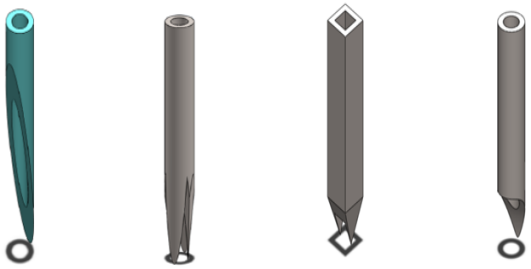

Fig. 2 Micro-needle tip designs

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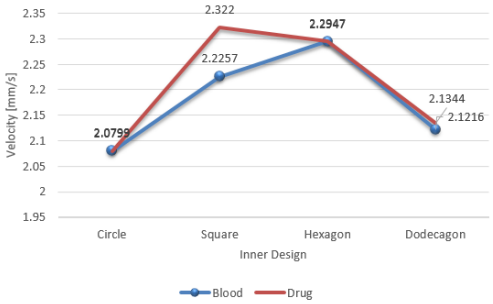

Fig. 3 Flow performances in micro-needle

Table. 3 and Table. 4 show the pressure obtained in drug and blood flow delivery simulation. The energy losses is then calculated using the Eq. 1 as shown in previous section.

In drug flow delivery, using square inner design has higher velocity compared to other designs. It shows that when square inner design is used, it has the lowest energy losses which is 1.41×10^{-3} mm along the microneedle. On the other hand, it also shows that when the value of velocity per area increases, the energy losses per area has lower value respectively.

In blood flow delivery, using hexagon inner design has higher velocity compared to other designs. It shows that using hexagon inner design, lower energy losses can be obtained which is 1.41×10^{-3} mm along the microneedle. On the other hand, it also shows that when the energy loss per area decreases, the velocity per area has lower value respectively.

Fig. 4 and Fig. 6 show the relationship between velocity and energy losses, E_L in the micro-needle. Fig. 5 and Fig. 7 show the relationship between velocity per area and energy losses per area in the micro-needle. These figures can be summarized as that wall interaction is higher than the interaction's area which are applied to the inner designs of the micro-needle.

As the fluid flows through a channel, the fluid experiences some resistance due to some energy losses, usually caused by secondary flows. As time passes, the increase of viscosity affected the velocity in a channel. Mainly, the viscosity causes loss of energy in the flows due to friction which is related to the Reynolds number for the fluid flow, surface roughness of the channel and the geometry of the channel.

In blood flow rheology, the elevation in red cell hematocrit, eventually increase the blood viscosity. Thus, increase the resistance to blood flow. If clotting mechanisms are stimulated in the blood, platelet aggregation and interactions with plasma proteins occur. This leads to entrapment of red blood cells and clot formation, which dramatically increase the blood viscosity. The higher viscosity of the fluid, the higher resistance to flow because the fluid's particle have more force attraction between them. These leads to be having more cohesion and internal friction which how often the particles of a fluid slip past each other. Thus, decreasing the flow rate of the fluid's flow [15]~[17].

The relationship of velocity-energy losses can be further explained in the relationship of V/A-EL graphs for both drug and blood delivery. The highest velocity obtained are square for drug delivery and hexagon for blood delivery. The fluid-wall interaction has been minimized or exterminated, thus, the energy losses is small in these microneedles size. The value per area is generalized for all microneedle regardless of its inner design parameters. In drug delivery, square inner design has smallest value in velocity per area but in order to achieve the smallest value in energy losses per area, the inner design has to be circle. In blood delivery, hexagon inner design has smallest value in energy losses per area but in order to achieve the smallest value in velocity per area, the inner design has to be square.

Table. 1 Drug Flow Performance

Inner design	Material	Diameter [mm]	Length [mm]	Velocity [mm/s]
Circular	Polysilicon	0.10	50	2.0799
	Titanium			
Square	Polysilicon	0.15	50	2.3220
Hexagon	Polysilicon	0.10	50	2.2947
Dodecagon	Polysilicon	0.10	50	2.1344

Table. 2 Blood Flow Performance

Inner design	Material	Diameter [mm]	Length [mm]	Velocity [mm/s]
Circular	Polysilicon	0.10	50	2.0799
	Titanium			
Square	Polysilicon	0.15	50	2.2257
Hexagon	Titanium	0.10	50	2.2947
Dodecagon	Polysilicon	0.10	50	2.1216

Table. 3 Drug Flow Relationship Performance

Inner design	Pressure [Pa]	Energy Losses, $E_L, 10^{-3}$ [mm]	E_L/A [1/mm]	V/A [1/mms]
Circular	1.61	1.61	0.0512	66.62
Square	1.41	1.41	0.0627	103.2
Hexagon	2.07	2.07	0.0727	80.43
Dodecagon	1.69	1.69	0.0636	80.32

Table. 4 Blood Flow Relationship Performance

Inner design	Pressure [Pa]	Energy Losses, $E_L, 10^{-3}$ [mm]	E_L/A [1/mm]	V/A [1/mms]
Circular	6.16	5.81	0.1849	66.70
Square	5.15	4.86	0.2159	98.92
Hexagon	2.06	1.94	0.0681	80.43
Dodecagon	6.48	6.11	0.2301	79.85

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The painless microneedle designs are based on the maximum stress results between the micro-needle designs. This can be seen from Figs. 8 – 11. It shows that quadrupletip produce less stress than the 10°, D3-2 and D6 microneedle tip designs.

Table. 5 shows the simplified way to view the differences of each micro-needle resulted when penetrates the rubber for the maximum strain and displacement result of each micro-needle.

It shows that the highest value produced by 10° micro-needle compared to quadrupletip micro-needle which produced less value of strain result but slightly higher than D6 tip. This means that the painless needle use less strain in order to penetrate the surface of the rubber.

The maximum value of displacement result is D6 tip micro-needle has the highest value then followed by quadrupletip micro-needle and slightly higher with D3-2 and 10°. The results show that the painless needle should have minimum value of displacement and penetrate faster.

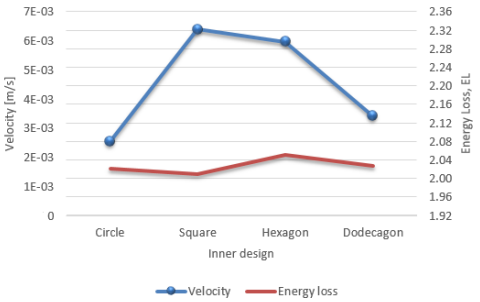

Fig. 4 Velocity- E_L relationship in drug flow

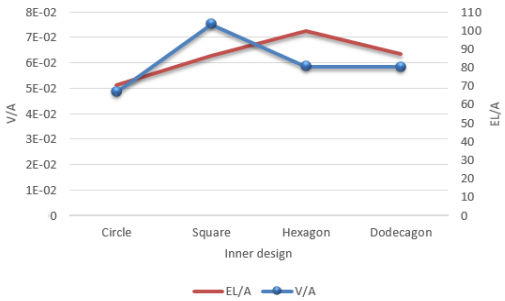

Fig. 5 V/A-E_L relationship in drug flow

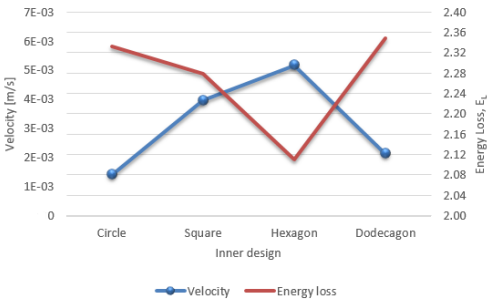

Fig. 6 Velocity- E_L relationship in blood flow

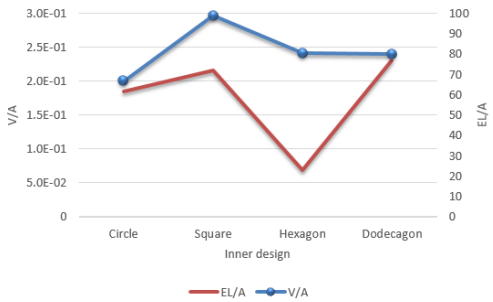

Fig. 7 V/A-E_L relationship in blood flow

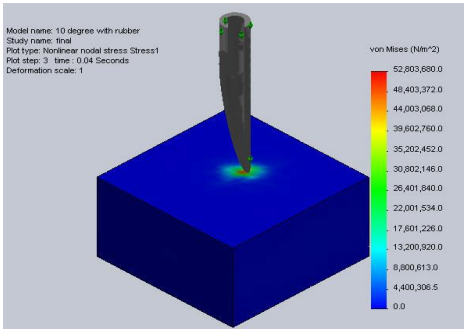

Fig. 8 10° Micro-needle penetrating rubber

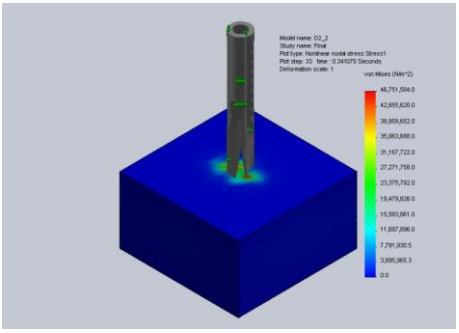

Fig. 9 Quadrupletip micro-needle penetrating rubber

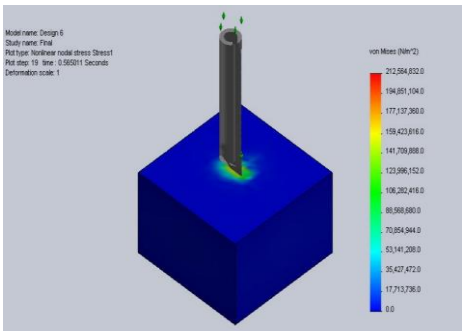

Fig. 10 D3-2 micro-needle penetrating rubber

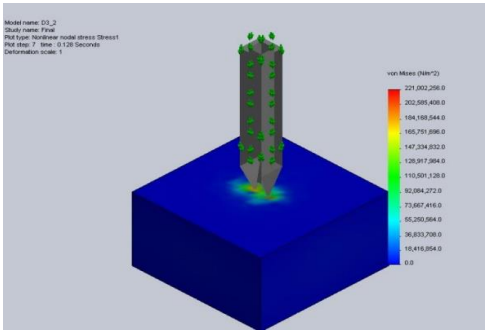

Fig. 11 D6 micro-needle penetrating rubber

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Table. 5 Comparison of 10°, Quadruple, D3-2 and D6 tip micro-needle

Micro-needles		
Stress [N/mm^2]	52.804	46.752
Strain [mm]	2.182 x 10^{-2}	2.167 x 10^{-2}
Displacement [mm]	2.000 x 10^{-2}	1.705 x 10^{-1}
Micro-needles		
Stress [N/mm^2]	221.00	212.56
Strain [mm]	1.156 x 10^{-1}	8.953 x 10^{-2}
Displacement [mm]	6.400 x 10^{-2}	2.825 x 10^{-1}

4. Conclusion

This paper concludes that hexagon inner structure of microneedle has better delivery for blood, while, square inner structure of microneedle has better delivery for drug. It also shows that quadrupletip microneedle is the best design for pain optimization with lowest maximum value of stress compared to other designs. This implies that the designs had improved the insertion performance and potentially the painless blood withdrawal efficiency. Future works can be done by using quadrupletip microneedle attached to a micropump in calibration with medical industry.

5. Acknowledgement

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