Capillary Rise Modeling and Fabrication of Crown-shaped Microneedle Array for Blood Extraction

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Abstract

Crown-shaped microneedle or quadruplets-microneedle fabricated by synchrotron radiation deep x-ray lithography for blood extraction was developed and has been introduced recently. Since the phenomenon driven a blood extraction process of the quadruplets-microneedle is capillary force, a study of capillary phenomenon or surface tension to suit our microneedle shape was pursued. In the array of quadruplets-microneedle, there were four open-sided grooves connected to all neighbored needles. The higher the capillary rises, the faster the liquid flow through the channel. A geometric calculation of the volume of liquid that can be stored in the microneedle suggests that without the grooves, total amount of liquid extracted by the array of 1024 microneedles is about 0.5 μl whilst the amount of liquid increasing to 0.9 μl with the groove arrays. The flow of liquid by capillary rise was modeled by two configurations of the groove of microneedle; the open-side groove and vertical rectangular tube which is in the center of the microneedle connecting the 4 open-side grooves. The result of simulation was conformable to the experimental data. The numerical simulation method of blood extraction process using the microneedle is discussed.

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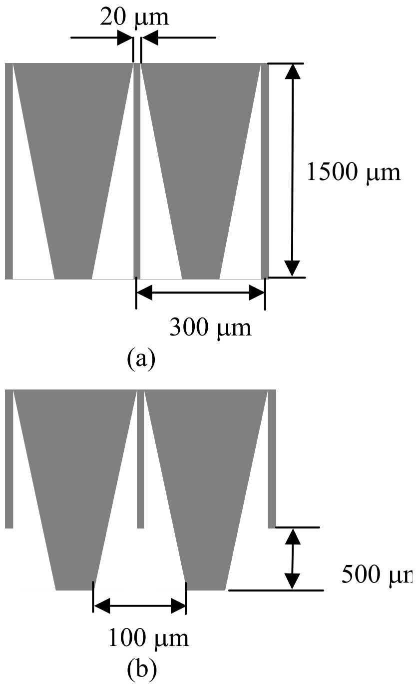
Since the phenomenon driven a blood extraction process of this quadruped tips is capillary

1. Introduction

The study on appropriate shape of X-ray mask for liquid flow in the groove of crown-shaped microneedle was required in order to enhance the maximum volume of liquid stored in the grooves. The crown-shaped miconeedle was first reported in 2004 [1]. In this work, two types of triangular mask-patterns have been suggested; the double right triangles, and u-shape triangle. Figure 1 shows the mask-patterns and dimensions. The purpose of this study is to model the capillary phenomena by computation of capillary height effects on internal flow of liquid extracted by the quadruplets-microneedle. For the structure fabricated by double right triangular pattern results as a 90º bent path connected the horizontal groove and the open-quadruped channel between each spike of the microneedle. The structure resulted from using u-shape triangle is a 60º bent path. Figure 2 illustrates the SEM photos of microneedle fabricated by both types of triangular mask-patterns.



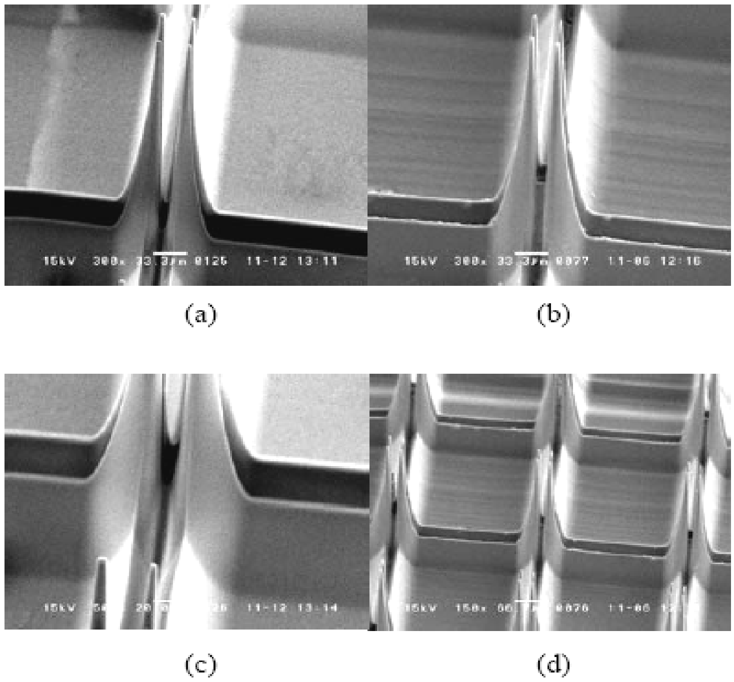


Fig 1.(a) double right triangles mask and (b) u-shape triangle mask with dimesions

Fig. 2. SEM photos of microneedles fabricated by triangles and (b) u-shape triangle, (c) The close up image of double right triangles pattern and (d) array of u-shape triangle pattern.

2. Capillary theory and modeling

The numerical simulation method of blood extraction process using the microneedle is discussed in this section. The main working force for extracting blood by the crown-shaped microneedle is, capillary force. The surface tension effect has been introduced with the help of a dynamic contact angle instead of a static one as schematically depicted in Fig. 3. The figure shows two types of flow with regard to the surface tension effect : a pressure-driven flow with a negative(flow hindrance) effect and a surface tension-driven flow with a positive(flow enhancement) effect. Depending on the positive or negative effect, the range of θ varies : $90^\circ < \theta \leq 180^\circ$ for the negative effect, $0^\circ \leq \theta < 90^\circ$ for positive effect. $\theta = 90$ is the special case when the surface tension has no effect on the flow.

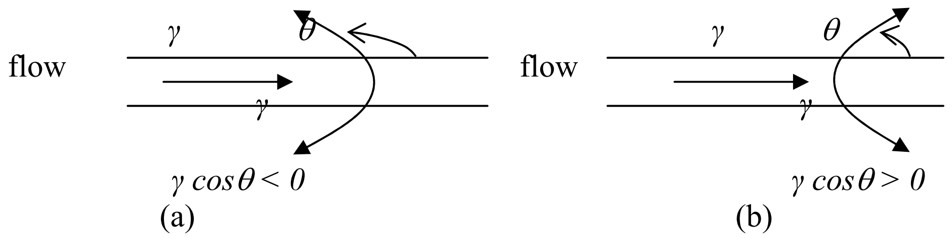


Fig. 3 Flow types : (a) pressure driven flow and (b) surface tension driven flow

To consider the capillary rise, the basic capillary equation for circular tube [2] in a reduced form is shown in Eqs. 1.

$$\text{Capillary rise} \quad h = 2\,\gamma \cos\theta \,/\, \rho g r \tag{1}$$

r is the capillary radius, h is the capillary height, θ is angle of the edge of blood surface against a groove wall and γ is the surface tension.

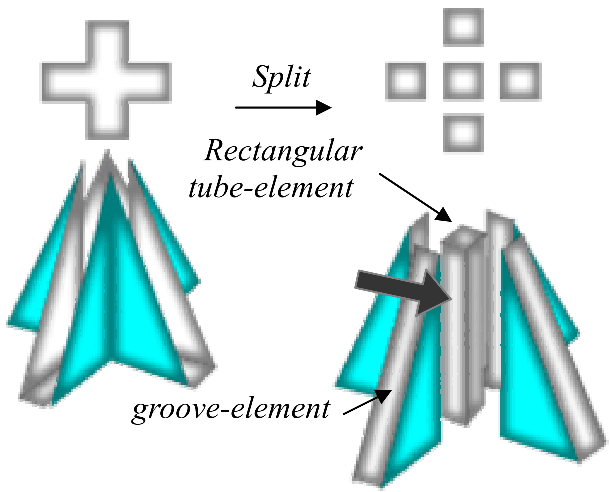


Fig. 4 The two elements split for two different capillary phenomena.

However, the equation confirms only the flow of liquid in a long cylindrical capillary. Thus, we split the capillary phenomena into 2 cases; capillary rise in rectangular tube and capillary flow in grooves. The separated two elements are shown in the geometry in Fig. 4.

2.1 Rise in a Rectangular-tube Element

A conduit of rectangular cross-section could be modeled by a circular cross-sectional pipe with an equivalent hydraulic radius (R_h). The equation might be corrected by C_f. C_f is a correction factor determined so that the filling time of a surface tension driven flow in a circular pipe becomes the same as that in a rectangular channel. Eqs.1 is employed for the flow in circular tube. From a modification of Eqs.1 by the correction factor, the Eqs.2 is used in substitution for rectangular tube.

$$h = 2\,\gamma \cos\theta \,/\, \rho g R_h C_f \tag{2}$$

where, R_h is hydraulic radius of a non-circular duct calculated by width(W)*thickness(H)/(W+H). The correction factor C_f is calculated by the Eqs. 3

$$C_f = (2/3)(1 + H/W)^2 F_p \tag{3}$$

F_p is shape factor and equals to 1/16 for rectangular tube [3]. It is noted that in our case, W(width) = H(thickness) and refers to the distance between each spike of the microneedle and the value of W must be as small as possible whilst the volume of blood contained in the needle grooves is enough for a medical test. The possible smallest W is suggested to be 5μm since 8μm-diameter of red blood cell can smoothly pass through. For the white blood cell, the 20 μm-diameter of each cell has also been considered. Although the white blood cell is quite larger than red, it is less numerous (the ratio is around 1:700) and is normally warped.

2.2 Flow in a Groove Element

Contact angle has obvious influence in the capillary performance of the microgrooves. This angle varies with the working fluid, physics of the solid, and the characteristics of the contact surface. A larger contact angle, the bigger capillary force. The theory of capillary phenomena in grooves reported as the rectangular-parallel channel so far (Fig.5(a)). We enhanced the theory to fit our structure of quadruplets-microneedle. As shown in Fig. (b)The area of inlet is b and expanded as a function of height (or the length of microneedle). The three-dimensional study on capillary flow has been done by a simulation software MATLAB. The main steps for study of capillary phenomenon in crown-shape microneedle are; to obtain the capillary height, to calculate the capillary velocity and to find the capillary number for plotting the extracted volume of liquid.

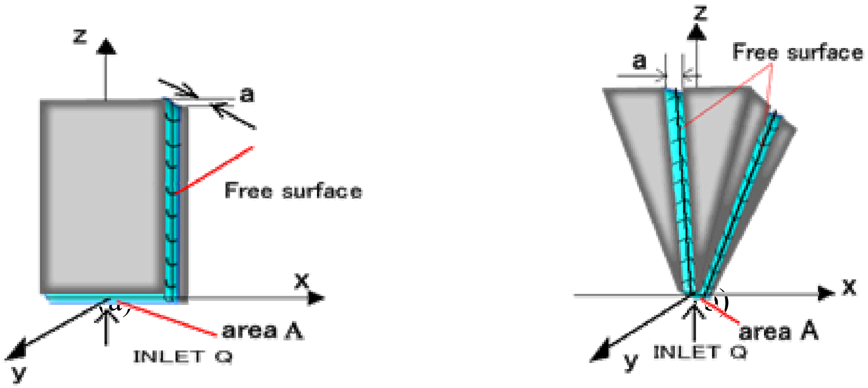


Fig. 5 The geometries of (a) channel formed by two parallel solid-plates and (b) grooves formed by 2 spikes of quadruplets-microneedle

(1) Capillary Height

If a corner formed from two solid plates is put in contact with a wetting liquid, a meniscus generally rises inside the corner (Fig. 5). Different questions can be solved, such as the conditions for observing a rise and the final capillary height and shape of the meniscus. A balance between the Laplace pressure and the hydrostatic pressure can be written,

$$\gamma / R = \rho g z, \tag{4}$$

R is the radius of curvature of the interface at a height z; γ and ρ are the liquid surface tension and density; and g is the acceleration of gravity. R is geometrically related to the distance d between the corner and the interface,

$$d = R[(\cos\theta/\sin(\alpha/2)) - 1], \tag{5}$$

where α is the corner angle that equals to 90º for our groove and θ is the contact angle by liquid/solid. The distance *d* is positive (which means that the liquid rises) if the angles verify the classical relation of Concus and Finn [4]. Combining together Eqs.4 and Eqs.5 shows that the shape of meniscus is hyperbolic, as reported in [5, 6],

$$d \sim 1/ z\kappa^2 \tag{6}$$

where 1/κis a constant and equals to √(γ/ρg).

(2) Capillary Velocity

Assume that the capillary driven two-phase flow in a corner described by a Poiseuille type equation [7], is similar to the flow in a groove. Although the groove is rectangle, an opening side causes the error by governing the equation of flow in rectangular tube. Thus, the governing equation can be written as,

$$\frac{d(\rho HLu)}{dt} = 2\gamma \cos\theta + \Delta P\, H - \frac{12\,\mu L}{H} u \tag{7}$$

A transient solution derived by noting *u* = *dL/dt*, the Eq.7 becomes

$$u = \frac{A(1-\exp(-Bt))}{2BL} \tag{8}$$

$$A = \frac{4\gamma\cos\theta + 2\Delta PH}{\rho H} \tag{9}$$

and

$$B = 12\mu/\rho H^2 \tag{10}$$

where μ is dynamic viscosity, γ is the surface tension *L* is position of free surface front along the groove, *H* is width of the groove. For the computation of capillary velocity, the result from simulation based on Eqs.8 will be shown in the later section.

(3) Capillary Number

Volume of liquid dragged into the groove of microneedle can be calculated by an analytical estimate[ ],

$$V = (\pi/3) \tan\theta\,[(a \cos\theta) / (\cos\theta + \sin\theta + \sin(4\sqrt{Ca} - \theta)]^3 \tag{11}$$

where θ is contact angle, *a* is width of groove and capillary number is defined by,

$$Ca = \frac{\text{viscous force}}{\text{surface tension force}} = \frac{2\gamma}{(\rho \upsilon^2 a)} \tag{12}$$

γ is surface tension and υ is capillary velocity.

3 Results

A contact-angle measurement has been done for measuring the angle between liquid, Aniline Blue Solution (Wako Chemicals Japan) and solid, PMMA sheet. Since the ionic condition of the wall surface material effects the wettability, the surface condition of a solid is a factor to define whether the contact angle is obtuse or acute contact angle. The solution was chosen since its viscosity is similar to that of human blood (about 0.004 Pa.s). It has been decided that the trial should not be done directly with the human blood from the beginning since the test can not be completed in a short time and a few times. A testing with human blood will be performed further to study on the bio-compatibility and excluded in this work.

The PMMA microgrooves with several diameters in a range of 25μm - 125μm and length of 30 mm have been fabricated by excimer-laser for testing of capillary rise. Since the smallest size of square-aperture for our excimer-laser is 25 μm, the fabrication of a long groove can not be smaller than 25μm(unless using X-ray lithography yet the cost of mask production is extremely high). The grooves used in the experiment have been considered as a square section ($\alpha = 90^o$) brought in contact with a reservoir of liquid. We have measured the final capillary level, h reached by the central meniscus, using aniline blue solution which wets the PMMA with $\theta = 61^o$, h is plotted in Fig. 6 as a function of the inverse of the size of the groove. The tendency is found to be linear, as in common capillary rise.

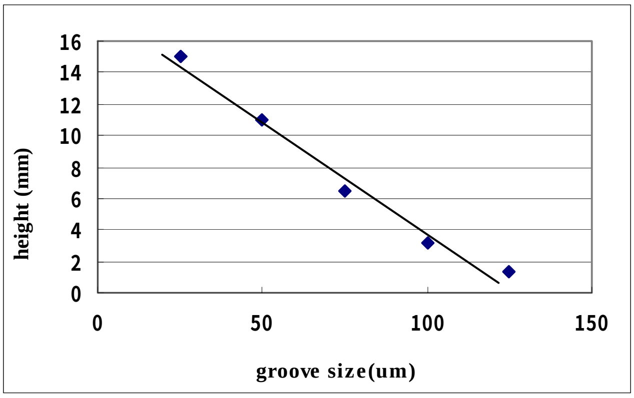


Fig. 6 Plot of capillary height(h) against the size of groove.

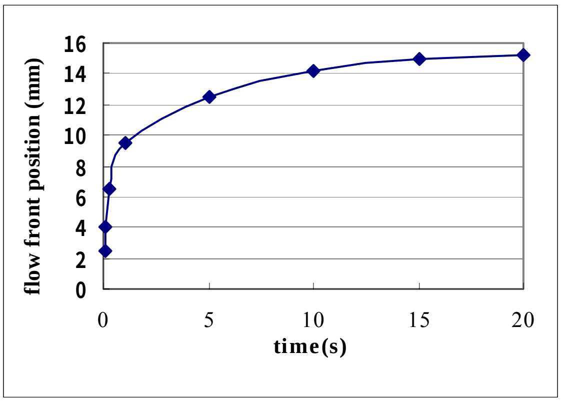


Fig. 7 Plot of flow front position against the time after rising of aniline blue sol. in 25μm-width groove

The result from the above plot with the approximately drawn line conforms the Eqs. 1 that the capillary height is a function of inverse size of grooves as well as radius of circular tube. By the result, the surface tension γ can be computed by Eqs.4.

The velocity plot with the position of flow front(L) is given in Fig. 7. The experiment was performed by the same liquid(Aniline blue solution) on the microgroove whose H = 25μm. A video camera was used then the data has been collected without affecting the liquid flow by the high temperature from light-source of optical microscope. The position plot is appeared to be exponential function to the time.

The PMMA after exposure by X-ray and developed by GG developer appeared to be more hydrophilic compared to the one before exposure, based on the experiment. In this study, we take the latter case(hydrophobic) into account since the final material array will be the PMMA after a plastic injection from Nickel mold, not as the master one after an X-ray exposure. The contact-angle of Aniline Blue Solution/PMMA substrate is approx. 61^o (measured by charged couple device or CCD and camera with imaging lens).

5. FLOW SIMULATION

Refer to Fig. 3 the quadruplets-microneedle has been spilt into 4 grooves. A split-element has been taken to simulate. By experimental data reduction, MATLAB can solve the volume flow rate(Fig.9). The data plotted in Fig. 7 provides time interval (Δt) and height (H). An equation for solving the volume flow rate*(Q)* can be obtained from,

$$Q = V/\Delta t \quad (13)$$

V is the volume of liquid drawn into the groove.
Since $V = AH$ and the changes in H by the time different also make changes in area A. Relationship between A and H is derived by putting Max.H and Max.x to a linear equation so that;

$$H + 7.5x = 300 \quad (14)$$

The groove width, a is used in gaining an equation of Q,

$$Q = aH\,(300\text{-}H)/7.5 \quad (15)$$

Thus,

$$Q = a\,(300\Delta H\text{-}\Delta H^2)/7.5\Delta t \quad (16)$$

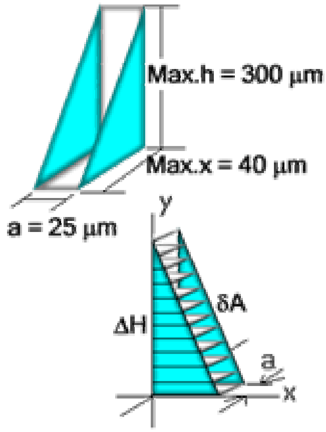


Fig. 8 Geometry of a groove in the modeling

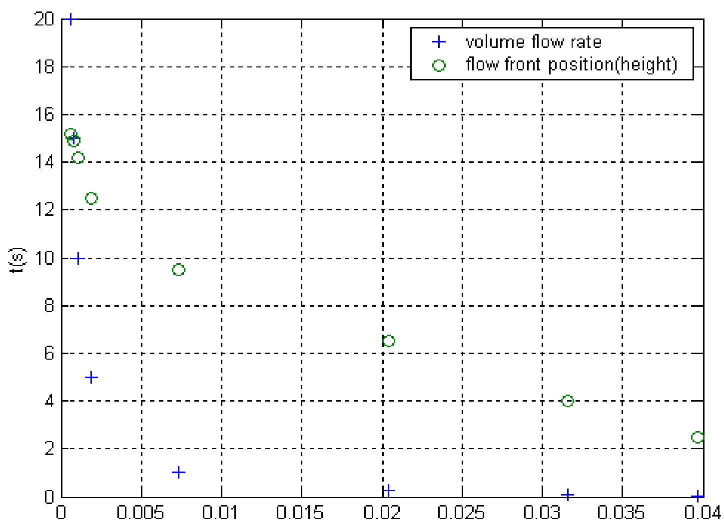


Fig.9 Volume flow rate plot against time and height

A result from the flow computed by MATLAB, value of Ca has been also calculated by Eqs.11 and resulted Ca = 0.0055. The calculation was done as an inverse step; V(volume of liquid dragged into the groove) obtained previously has been used for finding the Capillary, Ca then the surface tension(γ) can be calculated by Eqs.12. Surface tension of aniline blue solution in contact with air at 0.068 N/m was finally obtained.

6. CONCLUSION

The crown-shaped microneedle array of quadruplets-microneedle has been fabricated and simulated. Some unknown parameters affected to the capillary phenomena were obtained. The microneedle is expected to be used by coupling with some bio-sensors, e.g. ion-sensors, glucose sensors, and etc. Therefore, the blood sample after extraction is supposed to be stored inside the microneedle grooves and be ready to perform a bio-medical test on its array.

In the array of quadruplets-microneedle, the grooves are connected to all neighbored needles in the array. The higher capillary rise, the faster liquid flow through the total channel. A geometric calculation of the volume of liquid that can be stored in the microneedle suggests that without the grooves, total amount of liquid extracted by the array of 1024 microneedles is about 0.5 μl whilst the amount of liquid increasing to 0.9 μl with the groove arrays. The dosage data must be changed from time to time due to the life cycle of X-ray. The Aniline solution could be poison if the amount being intake is high. As a result from theoretical model, the capillary number and surface tension γ has been defined by the assist of MATLAB.

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