Fluid Dynamics underlying Morphogenesis

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Abstract: It is well-known that the morphogenesis of multi-cellular organism such as sea chestnut and frog, the cleavage after fertilization, is dominated by some types of proteins such as actin microfilament. However, if these proteins are not delivered to the correct places in cell, accurate cell divisions can not be achieved. Computational fluid-dynamics with a higher-order of accuracy, approximate solutions of the Navier-Stokes equation, reveals the reason why these proteins for structural development can be carried to appropriate positions.

Keywords: Cleavage plane, Computational fluid dynamics.

I. INTRODUCTION

Developmental biology and Topobiology [1, 2] reveal that the molecules such as microfilaments are necessary for the cell-division processes of multi-cellar systems. However, people can not explain the reason why cell divisions accurately occur at the fixed positions inside cells. Researches based on physics, i.e., mechanics, are necessary to clarify the mechanism underlying accurate delivery of microfilaments.
Fluid mechanics clarifies the early stage of morphogenesis, because seventy percents of contents in life are water.

II. HYPOTHESIS

It is well-known that first cleavage plane after fertilization, at which the ovum are divided into two cells, is decided by the point where sperm enters into the mother cell. [1] How will the second cleavage plane toward 4-cell system be determined?
Figure 1 shows the cleavage between 2-cell and 4-cell of multicellular organism. Then, Fig. 2 demonstrates the wrong cleavage planes, which do no occur usually. We know that the second cleavage plane brings same sizes of cells for many multi-cellar organisms. [1] This is possible because microfilament for contractile ring generating cleavage plane is placed at the appropriate position.
We will show the hypothesis, which can explain the mechanism causing the accurate cleavage plane. Two small and black ellipsoids in ovum of Fig. 3 imply microfilaments for contractile ring. The microfilaments move to the center of ovum, because these microfilaments shorten in order to cut the cell. Then, liquid around the microfilaments also go to the center of cell, because of the viscous flow around the filaments. As the result, the viscous flows coming from the left and right hand sides collide at the center.
Next, the two flows collided must go to upper and lower positions of the cell, because of mass conservation law. The aqua flow generated with the first cleavage plane can not be stopped suddenly at the center of the cell, because of the inertia.
Thus, the filaments also go to upper and lower places according to the flows.
Present delivery of microfilaments to upper and lower positions inside the cell brings the second division to 4-cell stage, which is shown in Fig 1.

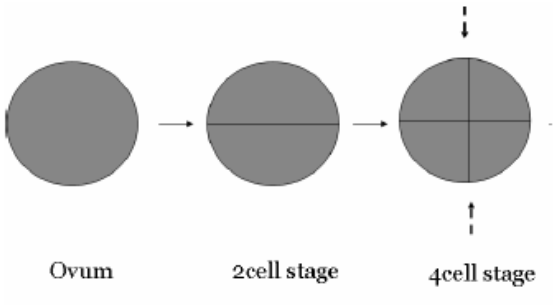

Fig. 1. Correct position of cleavage plane.

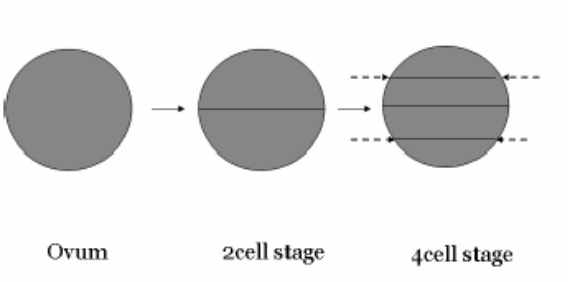

Fig. 2. Unreal position of cleavage plane.

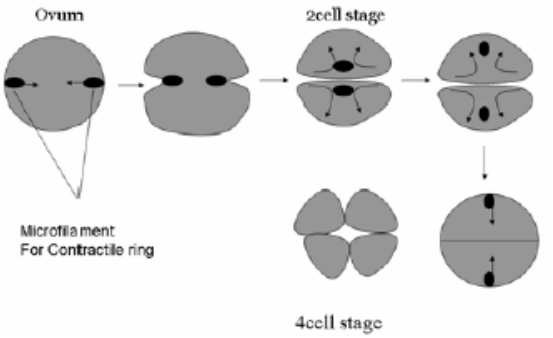

Fig. 3. Hypothesis which explains the position of cleavage plane.

III. NAVIER-STOKES EQUATION

Main parts inside cell are water. Then, fluid dynamics can explain the inevitability of some shapes of life such as jell fish, wing, nitrogenous bases, and so on. [4, 7, 8, 9, 10, 11] Moreover, it is well-known that water flow is described by the incomporessible Navier-Stokes equation. [5, 6] (See Eq. 1.)
Therefore, we analyze the flow field inside cell on the basis of the Navier-Stokes equation.

$$\frac{\partial u_i}{\partial t} + \sum_j u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{1}{\mathrm{Re}}\sum_j \frac{\partial^2 u_i}{\partial x_j^2}$$

$$\sum_i \frac{\partial u_i}{\partial x_i} = \varepsilon. \qquad (1)$$

where $p, x_i, t, and\ u_i$ denote dimensionless pressure, dimensionless Cartesian coordinate, dimensionless time, and dimensionless velocity vector, respectively.[i=1,2,3] Quantity Re implies Reynolds number. We assume that the moving speed of bio-molecules such as actin microfilament is equal to that of aqua-flow.
Thus, ε is the parameter for controlling the speed of cell division and the pattern of cell deformation. See Fig. 4. (If ε is zero, the flow incompressible without cell division.)

As is well-known, the Navier-Stokes equation is highly nonlinear. Thus, the analytical solution can not be obtained.
Here, we will solve approximately by using computer simulation based on the finite difference method with a higher-order of accuracy. [6]

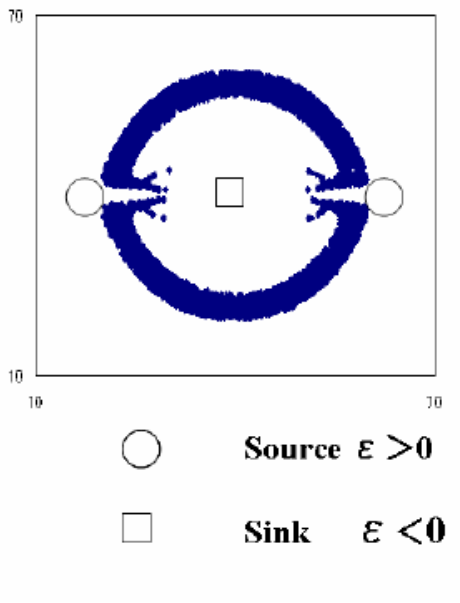

Fig. 4. Positions of sources and sink.

IV. COMPUTATIONAL RESULTS

Let's see Figs. 5 and 6, which are obtained by computations. We can see the temporal evolution from ovum to the early stage of 4-cell system. Computations are done in two-dimensional domain having 400 x 400 grid points. (Time increment is set to be 0.01, while grid size is 0.2 for each direction. Reynolds number, Re, is 10.0 in this research. Cell cycle is set to be about 1,000 time steps.)
It should be stressed that, in Fig. 6, a part of the cleavage plane at the center of the ovum naturally goes to upper and lower parts. Microfilaments for contractile ring divide into two direction of upper and lower, after going to the center of two-cell system. Then, we can see the flow runs toward the upper and lower parts at the center of Fig. 6.

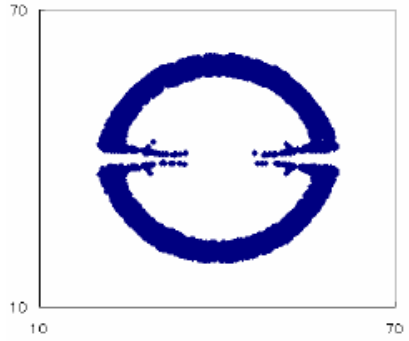

Fig. 5. Computation of the cell-division process between two-cell and four-cell (Initial stage. T=800).

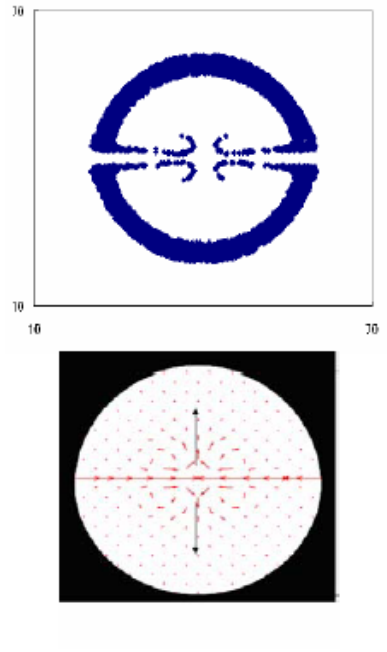

Fig. 6. Computation of the cell-division process between two-cell and four-cell (Middle stage. T=1000).

Fig. 7. Computation of the initial stage of four-cell system. T=1500.

After the first division of the cell shown in Fig. 6, we put two new sources of $\varepsilon > 0$ at the top and bottom of the cell.

Computational results shown in Figs. 7 and 8 represent the early stage of four-cell and eight-cell, respectively. Emphasis is placed on the fact that the flow for generating the cleavage plane of eight-cell can be observed.

V. BRAIN

In our previous report [12], we showed that brain shape is similar to the flow field structure in combustion chamber of piston engine for automotive systems, because neck and skull in human beings topologically correspond to intake-port and combustion-chamber, respectively. We can see that fluid dynamics explains both the first stage of the morphogenesis and the final stage of organs such as brain. In the near future, we will try to find the bio-fluid dynamics between the cleavage and organ.

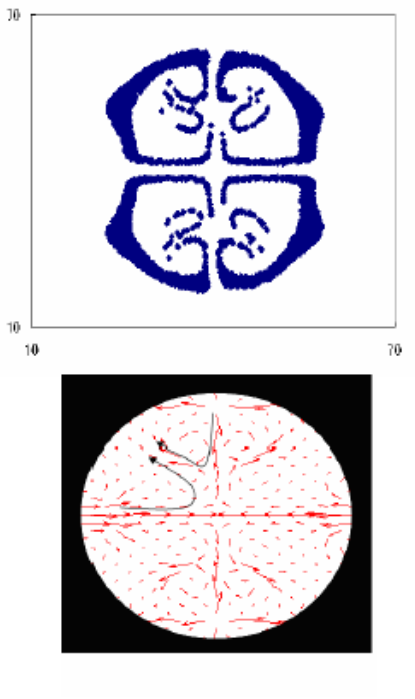

Fig. 8. Computation of the initial stage of eight-cell system. T=1800.

VI. CONCLUSION

Between ovum and eight-cell system, natural aqua-flow generated by microfilament carries the filament to the next starting point of division.

The motion of molecules inside cell is also dominated by fluid-dynamics. The flow strongly controls the morphogenesis of organism.

We propose the cyto-fluid dynamic theory clarifying the inevitability of micro-structures such as five nitrogenous bases, amino-acids, RNA structures, and so on. [5 -11] The present report explaining the stability of macro-structures such as cell division extends the cyto-fluid dynamic theory.

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