FINITE ELEMENT ANALYSIS OF CULTURED ENDOTHELIAL CELL UNDER PURE UNIAXIAL STRETCH: EFFECT OF CELL SHAPE ON STRAIN DISTRIBUTION

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INTRODUCTION

Endothelial cells in the arterial wall are subjected to fluid shear stress and cyclic deformation in the circumferential direction due to the periodic blood flow from the heart. Cellular responses to these mechanical stimuli must depend not only on the mechanical environment of the cell but also on the mechanical states in the internal region of the cell. Therefore, it is important to elucidate the strain state and the transmission of the deformation through the cell.

We performed a finite element analysis of an adherent cell on a substrate under biaxial stretch in the previous study [1]. An adherent cell model was developed on the basis of the shape and the material properties of the hyperelastic material model of a cell with a nucleus which was created by Caille et al. [2]. Our model was one eighth of an ellipsoid assuming the symmetry of the shape and the deformation.

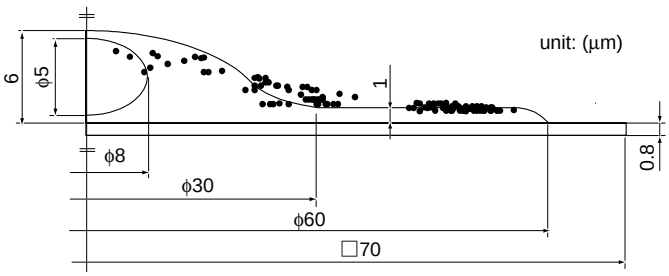
In this study we created another finite element model which had a "sunnyside up" shape with a bulge due to the nucleus in the central region and a thin and long skirt in the peripheral region (See Figure 1 (a)). Using this model we carried out finite element analysis of the strain and deformation in the cell to estimate the mechanical conditions in the cell as well as to validate the present model. We also analyzed the effect of the cellular shape on the transmission of the strain form the base to the top of the cell.

METHODS

We created a finite element model as shown in Figure 1 taking account of the position of markers used in the measurement by Caille [3]. The dimensions of the model were determined as Figure 1 (a). This model consists of the cytoplasm, nucleus and substrate. These components were assumed as Neo-Hookean material. The strain energy density function postulated in this study was expressed as

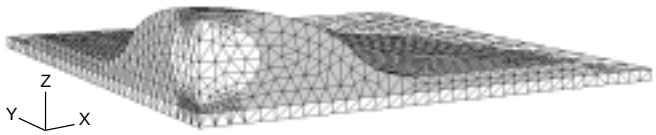
$$W = C(\overline{I}_1 - 3) \tag{1}$$

as a function of the first invariant of the deviatoric strain derived from the deviatoric deformation gradient $(\det \boldsymbol{F})^{-1/3}\boldsymbol{F}$ where C is a material constant and $\boldsymbol{F}$ is a deformation gradient tensor. The material constants in the cytoplasm, nucleus and substrate were assumed as 775 Pa, 5100 Pa and 775 kPa, respectively [2]. The substrate was stretched pure-uniaxially by 17.4% in the X direction with a deformation constraint in the transverse direction for the model in Figure 1. For models without nucleus to which was used to obtain Figure 5, the substrate was stretched in the same conditions as above. We utilized a pre/post processor of ABAQUS/CAE and a solver of ABAQUS/standard ver. 6.2 (H.K.S., Inc., U.S.A.) for the finite element analyses. The present model has 17868 elements and 28422 nodes. The elements type is 10-node quadratic tetrahedron hybrid with a linear pressure.



(a) Dimensions of the model. The dots denote the position of the markers in the strain measurement by Caille [3].

(b)



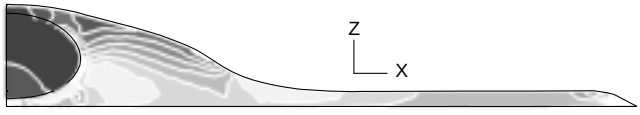
(b) Finite element model

Figure 1. Finite element model of a cultured endothelial cell which has a nucleus and is adherent to a substrate

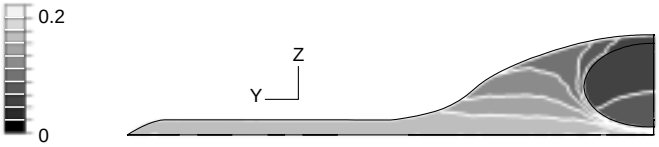
RESULTS AND DISCUSSION

Figure 2 shows the distribution of the engineering strain component in the X direction on the X-Z symmetric section (Figure 2 (a)) and on the Y-Z symmetric section (Figure 2 (b)) for the cell model of Figure 1 as a result from finite element analysis. The strain in the peripheral region of the cell is equal to that in the substrate to which the cell adheres, while the strain in the central region varies depending on the position in the cell. In the central region, the strain tends to decrease with an increase of the height of the position.

Figure 3 shows the distribution of displacement in the X direction in the cell and the substrate obtained from finite element analysis. Thickening in the central region causes nonuniform deformation as well as a decrease of the deformation with an increase of the height.



(a) X-Z symmetric section of the cell model



(b) Y-Z symmetric section of the cell model

Figure 2. Distribution of the engineering strain in the X direction under a pure uniaxial stretch to the substrate by 17.4%

Figure 3. Distribution of the displacement in the X direction on the X-Z symmetric section of the cell model under pure uniaxial stretch to the substrate by 17.4%

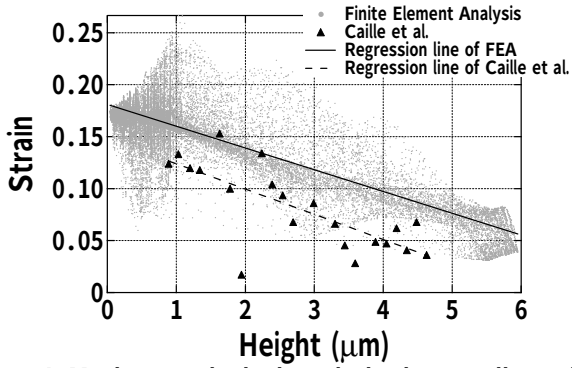


Figure 4. Maximum principal strain in the two-dimensional strain field on a plane parallel to the substrate surface ($\varepsilon^{(2)}_{max}$) for positions with various heights in the cell. The result was compared with the measurement result by Caille [3] for micro-beads embedded in a cultured endothelial cell.

Figure 4 shows the simulation result of the maximum principal strain in the two-dimensional strain field on a plane parallel to the substrate surface ($\varepsilon^{(2)}_{max}$) for positions with various heights in the cell. The strains $\varepsilon^{(2)}_{max}$ obtained in the numerical simulation were compared with those in the experimental measurement by Caille [3] for a cultured endothelial cell on a substrate. Gray colored dots in the figure were obtained from the integration points of finite elements in the region of cytoplasm. A comparison between the simulation result and the measurement one shows that the measured strains were lower than those in the simulation. This may be due to the geometry of the cell, the mechanical properties and structure of the cytoplasm or the conditions of cellular adhesion to the substrate. Wang et al. [4] reported that the strain in the cell was 77% of the strain in the substrate under equibiaxial stretch to the substrate by 10%. The present elastic continuum model tends to overestimate the strain, and the complete contact condition between the cellular base and the substrate surface may also give a large rate of transmission in the strain.

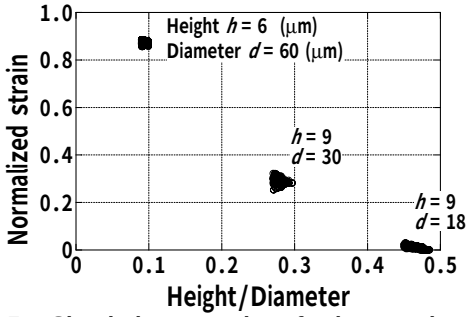


Figure 5. Simulation result of the strain ($\varepsilon^{(2)}_{max}(z)$) normalized using the applied strain to the substrate ($\varepsilon^{(2)}_{max}(z = 0)$) for various ratios of the cellular height to the cellular diameter on the substrate surface. The model does not have a nucleus. The dots plotted in the figure belong to the region of > 90% of the cellular height.

Figure 5 shows the simulation result of the strain in the X direction ($\varepsilon^{(2)}_{max}(z)$) normalized using the strain on the substrate surface ($\varepsilon^{(2)}_{max}(z = 0)$) for various ratios of the cellular height to the cellular diameter on the substrate surface. The model does not have a nucleus. The shape of the model was assumed as one eighth of an ellipsoid. The dots plotted in the figure belong to the region of > 90% of the cellular height. This result indicates that the strain on top of the cell gets closer to zero when the cellular height increases or the cellular diameter on the substrate surface decreases.

CONCLUSION

We carried out finite element analyses for the model of an adherent cell to the substrate which is subjected to pure uniaxial stretch. The results showed a tendency of strain reduction with an increase of the height and the effect of cellular shape (ratio of height to diameter) on the transmission of the strain to top of the cell.

This study was partly supported by a Grant-in-Aid for Scientific Research (C) from JSPS (No. 13650083) and a grant from ACT-JST.

REFERENCES

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