—**Original**—

Three-Dimensional Finite Analysis of the Optimal Alignment of the Tibial Implant in Unicompartmental Knee Arthroplasty

Katsumi Sasatani[1], Tokifumi Majima[1], Kohei Murase[2], Naoki Takeuchi[3], Takeo Matsumoto[3], Yasushi Oshima[1] and Shinro Takai[1]

[1]Department of Orthopaedic Surgery, Nippon Medical School, Tokyo, Japan
[2]Center for Industry-University Collaboration, Graduate School of Engineering Science, Osaka University, Osaka, Japan
[3]Department of Mechanical Science and Engineering, Graduate School of Engineering, Nagoya University, Nagoya, Japan

Background: Although unicompartmental knee arthroplasty (UKA) has become more common because of its good outcomes, several complications have been reported. Tibial implant alignment, an important cause of such complications, has been investigated; however, the optimal alignment of the tibial implant has not been determined. This study used 3-dimensional finite element analysis to investigate changes in stress distribution in the proximal tibia after UKA at multiple tibial implant alignments.
Methods: A 3-dimensional finite element model was created with CT digital imaging and communications in medicine (CT-DICOM) data from a medial osteoarthritic knee. Change in stress distribution of the tibial implant alignment on the coronal plane (middle position, varus 5°, valgus 5°) and sagittal plane (0°, 5°, 10°) under conditions of a loose boundary between implant and bone and no loosening was analyzed with 3-dimensional finite analysis.
Results: In the absence of loosening, the stress distribution was high at the lateral rim of the subchondral bone in the varus alignment model, and the high stress distribution moved from the anterior to the posterior position with posterior tilting from 0° to 10°. With loosening, the stress distribution was high at the proximal tibial medial cortex in the valgus alignment model.
Conclusions: To reduce UKA complications, the present findings indicate that the optimal alignment of the tibial implant is at the middle position on the coronal plane, with a posterior inclination similar to the original inclination on the sagittal plane. (J Nippon Med Sch 2020; 87: 60–65)

Key words: 3-dimensional finite element analysis (3D-FEA), unicompartmental knee arthroplasty (UKA), tibial implant, alignment

Introduction

The initial results of unicompartmental knee arthroplasty (UKA) were discouraging[1]. However, recent improvements in surgical technique and implant design, and identification of appropriate surgical indications, have increased UKA uptake. UKA results in rapid postoperative recovery and good kinematics—because of its less invasive surgical technique in preserving bone stock and bilateral cruciate ligaments—and patient satisfaction has recently been high[2,3]. Nevertheless, tibial implant loosening and subsidence and tibial medial condyle fracture are reported complications of UKA[4,5]. Although tibial implant alignment is a known cause of complications, few studies have investigated optimal alignment, which thus remains controversial.

This study used 3-dimensional finite element analysis (3-D FEA) to investigate the effects of coronal and sagittal tibial implant alignment on stress distribution in the proximal tibia and to identify the optimal tibial implant alignment in UKA.

Correspondence to Katsumi Sasatani, MD, Department of Orthopaedic Surgery, Nippon Medical School, 1–1–5 Sendagi, Bunkyo-ku, Tokyo 113–8603, Japan
E-mail: katsumi-sasatani@nms.ac.jp
https://doi.org/10.1272/jnms.JNMS.2020_87-202
Journal Website (https://www.nms.ac.jp/sh/jnms/)

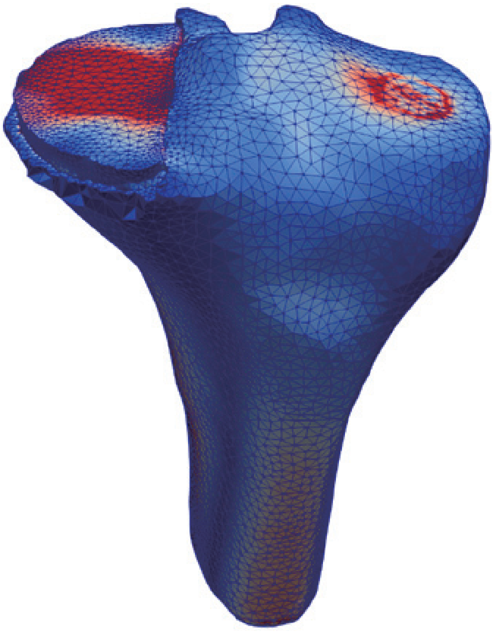


Fig. 1 The finite element model

Table 1 Material property

	Young's modulus (GPa)	Poisson's ratio
Tibial implant (Ti-6AL-4V)	100	0.32
Cortical bone	5	0.31
Cancellous bone	1	0.24

Materials and Methods

Three-D Finite Element Model

A 3-D finite element (3-D FE) model was created by using CT digital imaging and communications in medicine (CT-DICOM) data from a medial osteoarthritic knee (**Fig. 1**). Informed consent for publication was obtained from the patient. The lateral femorotibial angle was 180°, and tibial posterior inclination was 7°. The morphology of this model was relatively consistent with previously reported data[6]. The model consisted of 48,800 second-order tetrahedral elements with Mimics Ver. 21 (Materialise). The average length of the elements was 0.8±0.02 mm. The shape of the tibial component was also reproduced from a commercially available design, the Persona Partial Knee (Zimmer-Biomet, Warsaw, US; diameter, approximately 45 mm × 19.9 mm). We assumed the elasticity of each material and set Young's modulus and Poisson's ratio by using previously published values[7] (**Table 1**).

Alignment and Load

The alignment of the tibial implant was set on the coronal plane (middle position, varus 5°and valgus 5°) and sagittal plane (0°, 5°, 10°). The implant inclination angle was chosen in accordance with the study of Chtellard et al.[8]. The analytic model was completely fixed at the end of the distal tibia, and a total load of 1,500 N was applied equally to both condyles, parallel to the axis of the tibia. In this study, the interface between the tibial component and cutting surface was defined by using two conditions. Thus, the ideal fixation for which sufficient time had elapsed after surgery was assumed for the bonded interface. Conversely, the loosening condition was expressed as the contact-only (zero friction) setting in the finite element software.

Analysis

The Von Mises stress value expresses tensile or compressive stress on a given material loaded multidirectionally and was used to determine whether bone will yield when evaluating bone stress distribution, which is anisotropic and heterogeneous[9]. Because loosening of the tibial implant in UKA might be caused by collapse of the subchondral bone below it[10], changes in stress distribution at the subchondral bone of the osteotomy region were analyzed. In addition, change in stress distribution at the tibial proximal medial cortex was investigated because fracture of the tibial medial condyle ultimately results in failure of the tibial proximal medial cortex. Abaqus Ver. 6.3 (Fujitsu) was used for all analyses.

Results

Non-Loosening Condition

Tibial component alignment was adjusted on the coronal plane, and the Mises equivalent stress value for subchondral bone under the tibial implant was calculated in the absence of loosening. In the varus 5° model, stress concentration at the subchondral bone under the lateral rim of the tibial implant was higher than at the middle position in the valgus 5° model. In contrast, the stress distribution was lower at the anterior cortex and anterior subchondral bone of the keel in the middle-position model. In addition, stress distribution was lower at the posterior cortex and posterior subchondral bone of the keel in the valgus 5° model (**Fig. 2, 3**).

When the alignment of the sagittal plane was altered, the high stress distribution moved from the anterior to the posterior position when posterior inclination was changed from 0° to 5° and then 10°. In the posterior inclination 0° model, stress concentration was high at the anterior cortex (**Fig. 2, 4**).

When alignment on the coronal and sagittal planes

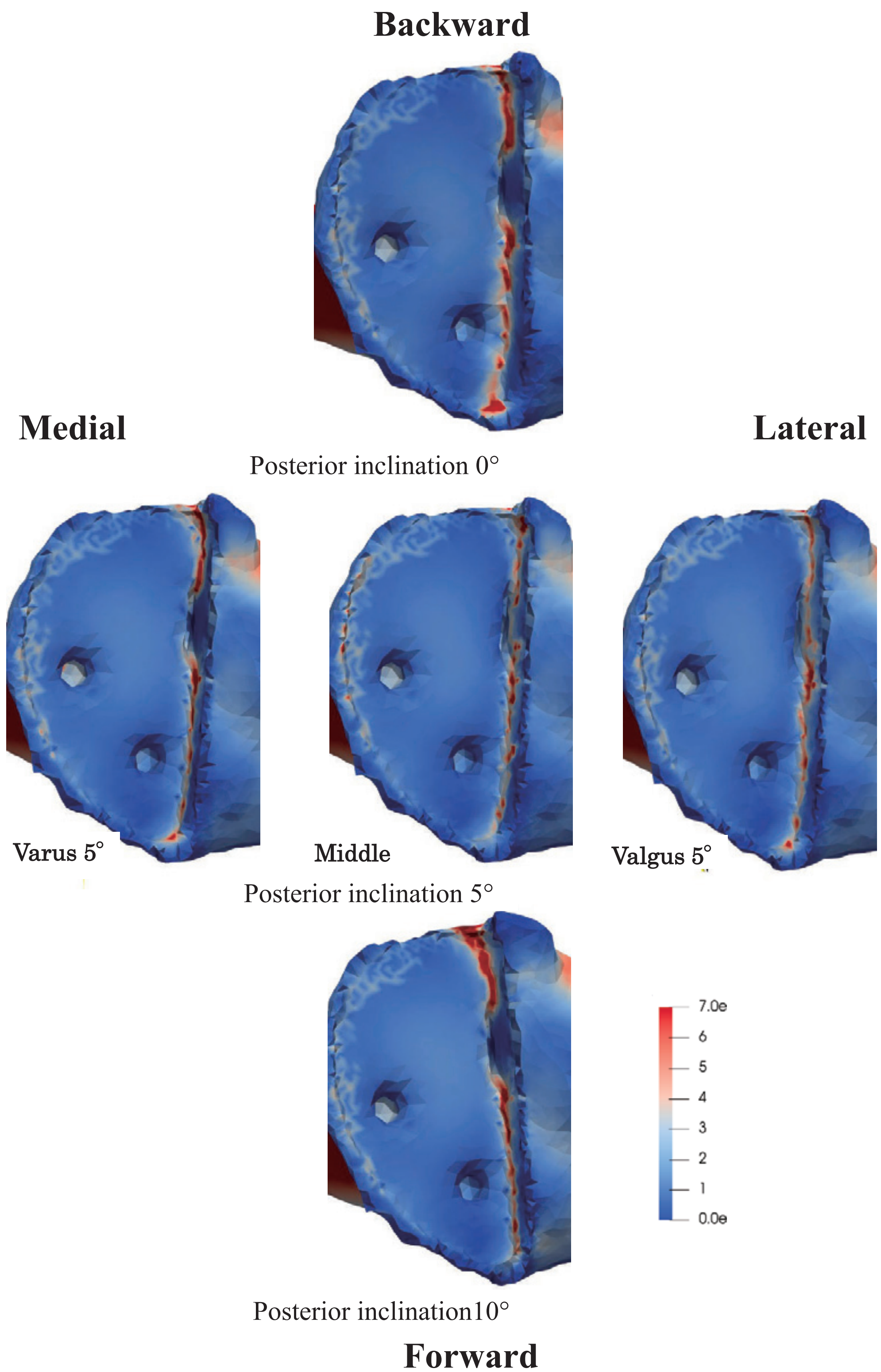


Fig. 2 Superior view of Von Mises stress distribution for subchondral bone at the bone-implant interface after removal of tibial implant (non-loosening model).

was adjusted, stress distribution in the medial cortex of the proximal tibia did not change.

Loosening Condition

Under the loosening condition, stress distribution in subchondral bone changed, but the trend was unclear. Stress concentration was higher at the medial cortex of the proximal tibia in the valgus 5° model than in the other models (**Fig. 5**).

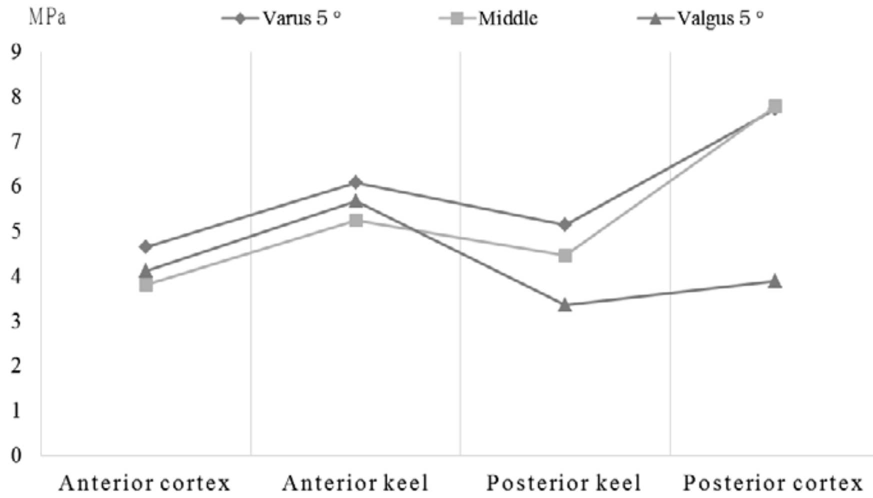


Fig. 3 Von Mises stress values for subchondral bone at the bone-implant interface (posterior inclination 5°; non-loosening model)

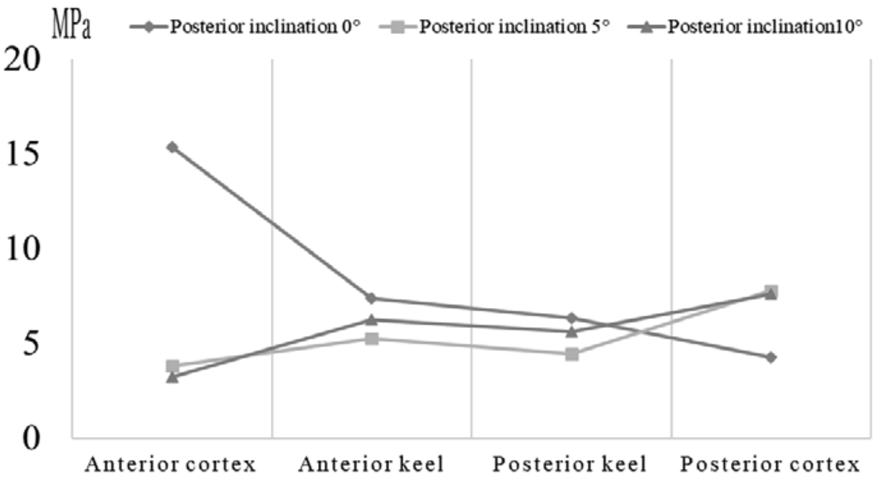


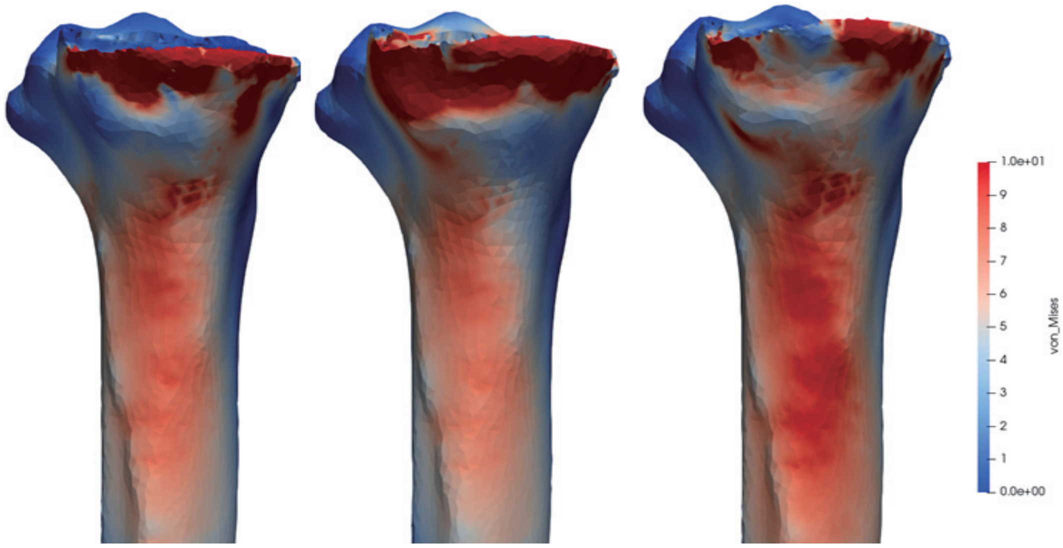
Fig. 4 Von Mises stress values for subchondral bone at the bone-implant interface (middle position; non-loosening model)

Discussion

Previous studies used FEA to analyze stress in the proximal tibia after UKA. Inoue et al.[4] reported that a varus alignment was better for preventing fracture of the tibial medial condyle after UKA. Using analysis of subchondral bone under the tibial component, Sawatari et al.[11] and Iesaka et al.[12] reported that a valgus alignment was preferable for obtaining a satisfactory stress distribution. Zhu et al.[13] reported that the middle position was best. Thus, the optimal alignment of the tibial implant in UKA is unclear.

In the present study, we analyzed the stress contribution of the proximal tibia by varying the coronal and sagittal alignments of the tibial implant. In the absence of loosening, stress tended to be higher on the lateral rim than on the medial rim under the implant overall. When coronal alignment was changed in the absence of loosening, stress concentration was high at the subchondral bone under the lateral rim of the tibial implant in the varus 5° model, most likely because medial inclination of the tibial implant moves the implant inward. Thus, it appears that varus alignment of the tibial implant should be avoided.

Stress distribution was high at the subchondral bone under the lateral rim when the tibial implant moved from an anterior to a posterior position (posterior inclination from 0° to 5° and then 10°). In particular, stress distribution was higher at a 0° alignment. The possibility of subsidence of the tibial implant is greater for a less posterior inclination. Many studies have reported that recreating the original posterior inclination of the tibia results in good outcomes[10,11,14]. In addition, positioning the tibial



Varus5° Middle Valgus5°

Fig. 5 Von Mises stress values for the medial cortex of the proximal tibia (posterior inclination, 5°; loosening model)

implant in an inadequately or excessively posterior inclination leads to implant loosening or subsidence[8,12]. Therefore, because the original posterior inclination of the tibia in the present 3D-FE model was 7°, it might be appropriate to reproduce the original posterior inclination in the tibia. However, analysis of a posterior inclination simulating vivo conditions was difficult because of the high number of elements, including the anterior cruciate ligament.

In the loosening condition, changes in the stress distribution in subchondral bone under the tibial implant were substantial, which suggests that the tibial implant was unstable. Nevertheless, no clear trend in stress distribution was noted. Meanwhile, stress concentration was observed at the proximal medial cortex of the tibia in the valgus model, which could lead to tibial medial condyle fracture.

Data for stress distributions for subchondral bone in coronal alignment suggest that a coronal inclination of the tibial implant from the middle position to a slightly valgus position is desirable. However, under conditions of loosening, the risk of tibial medial condylar fracture might be higher if stress concentration is high at the tibial proximal medial cortex in the valgus model. Thus, the middle position is the optimal alignment to reduce postoperative complications, as it decreases the possibility of loosening and subsidence of the tibial implant and tibial medial condyle fracture.

In determining optimal sagittal plane alignment, elements other than alignment of the tibial implant are important; however, past and present findings suggest that the limited posterior inclination of the original tibia should be reproduced.

This study has several limitations. First, the equilibrium state in vivo could not be reproduced under the restriction of soft tissues such as ligaments. Second, the load conditions were parallel to the bone axis of the tibia, an equal load was applied to both condyles, and the position of the lower limbs and alignment of the entire leg were not taken into account. Third, tibia data were collected from only one person and may not be generalizable. Fourth, this study shows no clear, direct relationship between the present findings and clinical results, including survival rates. However, our findings are consistent with previously reported clinical outcomes[6,8,14,15]. In the future, more accurate studies may be necessary. However, this is the first report to use 3-D FEA to identify the optimal coronal and sagittal alignment of the tibial implant in UKA.

In conclusion, a 3D-FE model was used to analyze changes in stress distribution in the proximal tibia while altering the alignment of the tibial implant in UKA on the coronal and sagittal planes. The optimal alignment of the tibial implant in UKA was the middle position on the coronal plane and the original posterior inclination on the sagittal plane.

Acknowledgements: We are grateful to Lawrence Frumson for reviewing the language of the manuscript.

Conflict of Interest: The authors declare no competing interests in relation to this study.

References

1. Lewold S, Robertsson O, Knutson K, Lidgren L. Revision of unicompartmental knee arthroplasty: Outcome in 1,135 cases from the Swedish Knee Arthroplasty study. Acta Orthop Scand. 1998;69:469–74.
2. Berger RA, Meneghini RM, Jacobs JJ, et al. Results of unicompartmental knee arthroplasty at a minimum of ten years of follow-up. J Bone Joint Surg Am. 2005;A87:999–1006.
3. Winnock de Grave P, Barbier J, Luyckx T, Ryckaert A, Gunst P, Van den Daelen L. Outcomes of a fixed-bearing, medial, cemented unicondylar knee arthroplasty design: Survival analysis and functional score of 460 cases. J Arthroplasty. 2018;33:2792–9.
4. Inoue S, Akagi M, Asada S, Mori S, Zaima H, Hashida M. The valgus inclination of the tibial component increases the risk of medial tibial condylar fractures in unicompartmental knee arthroplasty. J Arthroplasty. 2016;31:2025–30.
5. Pandit H, Murray DW, Dodd CA, et al. Medial tibial plateau fracture and Oxford unicompartmental knee. Orthopedics. 2007;30:28–31.
6. Nunley RM, Nam D, Johnson SR, Barnes CL. Extreme variability in posterior slope of the proximal tibia: Measurements on 2395 CT scans of patients undergoing UKA? J Arthroplasty. 2014;29:1677–80.
7. Murase K, Morita F, Yoshino N, Fukuda Y, Tsutsumi S, Ikeuchi K. Impact load transmission of human knee joint using in vitro drop-tower test and three-dimensional finite element simulation. J Biomech Sci Eng. 2007;2:218–27.
8. Chatellard R, Sauleau V, Colmar M, Robert H, Raynaud G, Brilhault J. Medial unicompartmental knee arthroplasty: Does tibial component position influence clinical outcomes and arthroplasty survival? Orthop Traumatol Surg Res. 2019;99:S219–25.
9. Li S, Demirci E, Silberschmidt VV. Variability and anisotropy of mechanical behavior of cortical bone in tension and compression. J Mech Behav Biomed Mater. 2013;21:109–20.
10. Taylor M, Tanner KE. Fatigue failure of cancellous bone: a possible cause of implant migration and loosening. J Bone Joint Surg Br. 1997;79:181–2.
11. Sawatari T, Tsumura H, Iesaka K, Furushiro Y, Torisu T. Three-dimensional finite element analysis of unicompartmental knee arthroplasty: The influence of tibial component inclination. J Orthop Res. 2005;23:549–54.
12. Iesaka K, Tsumura H, Sonoda H, Sawatari T, Takasita M, Torisu T. The effects of tibial component inclination on bone stress after unicompartmental knee arthroplasty. J Biomech. 2002;35:969–74.
13. Zhu GD, Guo WS, Zhang QD, Liu ZH, Cheng LM. Finite element analysis of mobile-bearing unicompartmental knee arthroplasty. Chin Med J (Engl). 2015;128:2873–8.
14. Franz A, Boese CK, Matthies A, Leffler J, Ries C. Mid-term clinical outcome and reconstruction of posterior tibial slope after UKA. J Knee Surg. 2019;32:468–74.
15. Barbadoro P, Ensini A, Leardini A, et al. Tibial component alignment and risk of loosening in unicompartmental knee arthroplasty: a radiographic and radiostereometric study. Knee Surg Sports Traumatol Arthrosc. 2014;22:3157–62.

(Received, June 4, 2019)
(Accepted, September 12, 2019)
(J-STAGE Advance Publication, October 15, 2019)