様式３

論　文　内　容　の　要　旨

氏　名　（　李 春雨　）	
論文題名	*In vitro* and *in silico* investigation of degradation of CAD/CAM resin composites by water absorption （吸水によるCAD/CAM用コンポジットレジンの劣化に関する*in vitro*/*in silico*研究）

論文内容の要旨

[Purpose]

CAD/CAM resin composites consist of a matrix resin and inorganic fillers treated with a saline coupling agent. However, degradation of the methacrylate group occurs when water is absorbed. Additionally, water ingress leads to hydrolytic breakdown of the bond between the silane and filler particles. This water-induced degradation negatively impacts the restoration longevity and mechanical properties. While these degradations have been reported qualitatively, quantitative details have not yet been revealed, especially in silane coupling layers. *In vitro* high-resolution imaging produces an accurate model reflecting morphological compositions. *In silico* homogenization enables identification of the main factor of physio-mechanical issues at the macro-scale. Therefore, the combination of *in vitro* and *in silico* approaches may enable quantitative investigation of the degradation of CAD/CAM resin composites by water absorption.

The aim of this study was to quantitatively evaluate how water absorption of the CAD/CAM resin composites affect the matrix resin and silane coupling layer using *in vitro* high-resolution imaging and *in silico* homogenization.

[Materials and Methods]

I. Investigation on the influence of water absorption on the bulk block and matrix resin

1. Water sorption test
   Disk shaped specimens of Katana Avencia P block (KAP) and experimental matrix block (EMB) (ϕ 14 × 1 mm) were fabricated. EMB was manufactured at the same temperature and pressure as KAP, excluding fillers. The water adsorption was measured according to ISO 4049:2019.
2. Three-point bending test
   Using the bar specimens (14 × 4.0 × 1.2 mm) of KAP and EMB, *in vitro*/*in silico* three-point bending tests were conducted to determine elastic moduli of before- and after-immersion groups.
3. *In silico* homogenization analysis
   KAP model consisting of spherical fillers and matrix resin was designed under the same filler contents of KAP. *In silico* homogenization analysis was conducted with two immersion conditions.

II. Verification of the physicochemical change of the silane coupling layer by water immersion

1. Nano-scale observation of the surface morphological change
   Bar specimens (7.0 × 4.0 × 1.2 mm) of Katana Avencia Block (KAB) were prepared. The specimens under before- and after-immersion conditions were observed by scanning probe microscopy (SPM).
2. Investigation of the amount of hydrolysis of the silane coupling layer
   After labelling the bar specimens of KAB with 1H,1H,2H,2H-perfluorooctyldimethylchlorosilane as a fluoride marker, the amount of fluoride-labeled hydroxyl group was investigated by X-ray photoelectron spectroscopy (XPS) by measuring the atomic percentage of F1s in the specimens for

before- and after-immersion groups.

3. *In silico* homogenization analysis
   Nano-scale CAD/CAM resin composite models with seven different coupling ratios were designed. Elastic moduli of each model were determined by *in silico* homogenization analysis.

III. Prediction of the amount of degradation of the silane coupling layer in CAD/CAM resin composite blocks

1. Three-point bending tests
   Bar specimens (14 × 4.0 × 1.2 mm) of KAB were prepared. *In vitro*/*in silico* three-point bending tests were conducted to determine elastic moduli of before- and after-immersion groups.
2. Reconstruction of the nano-scale model to reflect the filler shape
   Images of KAB were acquired using scanning electron microscopy/focused ion beam with a cryo preparation system. Acquired images were reconstructed to three dimensional model of KAB.
3. Prediction of the coupling ratio
   In silico homogenization analysis was conducted to determine elastic moduli of before- and after-immersion groups. By updating silane coupling ratio from 100% step by step, obtained elastic moduli of each group were compared to those obtained *in vitro*. The silane coupling ratio was determined when *in vitro*/*in silico* elastic moduli converged.

[Results and Discussion]

I. The water absorption values for KAP and EMB were 0.0183 and 0.0363 μg/mm3, respectively. The amounts of elastic modulus reduction by water immersion for KAP and EMB were 1.0 and 0.3 GPa, respectively. These results suggest that the matrix resin and other factors contribute to reducing the elastic modulus of CAD/CAM resin composites because the reduction amount of EMB as the matrix resin was only 0.3 GPa.

II. The SPM investigation revealed more degraded area in the specimen of the after-immersion group than the before-immersion group. The F1s peak in the XPS spectra and the greater atomic percentage in the after-immersion group than the before-immersion group suggests that hydrolysis in the silane coupling layer proceeded during water immersion. *In silico* homogenization analysis showed that a decrease in the elastic modulus occurred in conjunction with a decrease in the silane coupling ratio.

III. The model of CAD/CAM resin composites reflecting the nano-filler shape was successfully developed using cryo-electron microscopy. *In silico* homogenization analysis revealed that the elastic modulus of CAD/CAM resin composites under 100% silane coupled condition was 11.0 GPa, while the elastic modulus of KAB for before-immersion group was 8.2 GPa. These results suggest that the 100% silane coupling in KAB was not obtained in the manufacturing process. Additionally, silane coupling ratio of KAB decreased by 9.8% after 7 days water immersion.

[Conclusion]

Water absorption of CAD/CAM resin composites resulted in reduction of elastic modulus of matrix resin and hydrolysis of the silane coupling layer. The *in vitro* and *in silico* approaches established in this study were able to predict the silane coupling ratio of CAD/CAM resin composites, clearly demonstrating its decrease by water absorption.

様式 7

論文審査の結果の要旨及び担当者

氏　名　（　李　春雨　）			
論文審査担当者	（職）	氏　名	
	主 査	教授	今里　聡
	副 査	教授	十河　基文
	副 査	講師	谷川　千尋
	副 査	講師	権田　知也

論文審査の結果の要旨

本研究は、CAD/CAM 用コンポジットレジンの吸水による物性の低下を、マトリックスレジンとシランカップリング層への影響の観点から、*in vitro* と *in silico* での解析により評価したものである。

その結果、マトリックスレジンが吸水することによって CAD/CAM 用コンポジットレジンの弾性率の低下がもたらされるが、吸水によってシランカップリング層の加水分解も生じ、シランカップリングの割合の低下に伴って CAD/CAM 用コンポジットレジンの弾性率が低下することが分かった。また、*in silico* での均質化解析により、1 週間の水中浸漬によってシランカップリングの割合が 9.8%低下することが明らかになった。

以上の研究成果は、吸水による CAD/CAM 用コンポジットレジンの物性低下の原因を明確にし、また、それらによる影響を定量的に示すことに成功したものであり、本研究は博士（歯学）の学位授与に値するものと認める。