The Stress Distribution in Human Mandibular Premolar Region related to the Supporting Bone Quality: A Finite Element Study using a Micro-computed Tomography

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감사의 글

박사(博士)란 '널리 아는 것이 많거나 어느 부분에 능통한 사람'을 비유하여 하는 말이라고 합니다. 널리 아는 것도 많지 않고 어느 부분에 능통하지도 않은 사람인 제가 무사히 박사 논문을 마치고 학위를 받게 된 것은 많은 분들의 도움이 없었으면 힘들었을 것입니다.

본 논문이 완성되기까지 친형 이상으로 저를 지도해 주시고 이끌어 주신 지도교수 심준성 교수님과 논문 실험을 무사히 마칠수 있도록 도와주신 연세대학교 보건과학대학 의공학부 김한성 교수님께 각별한 감사의 마음을 전합니다. 보철과 전공의 시절부터 언제나 격려와 가르침을 주신 치과대학 보철과 이호용 교수님, 정문규 교수님, 이근우 교수님, 문홍석 교수님과 심사위원으로 수고해 주신 치과재료학 김광만 교수님께 감사의 뜻을 전합니다. 그리고, 치과의사의 길로 들어서면서 많은 가르침을 주신 담임반 교수님이신 구강병리학 교실 김진 교수님외 치과대학 여러 교수님들께 진심의 감사말씀을 전합니다.

마지막으로 저를 낳아주시고 길러주시고 언제나 신경 써 주시는 아버지, 어머니께 감사드리며, 저의 아내 신지영 선생과 귀엽고 착한 저의 딸 세현, 아들 세준이와 기쁨을 나누고 싶습니다.

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Abstract

The Stress Distribution in Human Mandibular Premolar Region related to the Supporting Bone Quality: A Finite Element Study using a Micro-computed Tomography

Various biomechanical studies have been accomplished to investigate the stress distribution within the tooth and to reveal the interrelationships between occlusal overloading and abfraction. However, those studies were executed without consideration of the complicated microarchitecture of tooth and supporting bone. The aim of this study was to generate the two dimensional micro-finite element models that reflect the microarchitecture of tooth and supporting bone and to examine the stress distribution in the tooth related to various bone quality.

A mandibular specimen with a first premolar was scanned using micro-computed tomography. With the scanned images, two dimensional micro-finite element models of a premolar and supporting bone of three different bone qualities (dense, intermediate, and loose bone model) were produced. A vertical and a horizontal load of 100N each were applied to the buccal cusp tip and the stress distribution within the tooth was analyzed.

The stress was mostly concentrated on buccal cervical portion and there was no difference in stress distribution pattern among three models of different bone quality.

It was possible to produce two dimensional micro-finite element models based on digital images from the micro-computed tomography, and to allow more accurate interpretation of the stress distribution pattern in a tooth than with previously available methods.

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Key Words: stress distribution, tooth, supporting bone, non-carious cervical lesion, abfraction, micro-computed tomography, finite element study

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I. INTRODUCTION

The non-carious cervical lesion (NCCL), in the absence of decay, is characterized by the loss of tooth tissue at the cemento-enamel junction (CEJ) typically with wedge-shaped sharp margins or broad saucer-shaped smooth margins.[1-3] Prevalence and severity of these lesions were known to increase with age.[3-7] The NCCL does not lead to clinical problems in some patient, but it has been known to cause tooth hypersensitivity in others. [3, 8, 9] In severe cases, the lesions may affect pulp vitality and cause crown fracture.[3, 8, 9]

Traditionally NCCLs were considered to occur due to tooth brushing abrasion, or acid erosion by dietary sources, environment, and gastric regurgitation.[3, 10-13]

However, with these mechanisms, it was difficult to explain the sharp wedge-shaped cervical defects occurring on a single tooth. In the past 20 years, a tooth flexure theory or an occlusal stress theory has been accepted as a mechanism for wedge-shaped cervical tooth loss.[3-6, 14, 15] The occlusal loading causes deformation and flexure of a tooth, resulting a disruption of enamel crystals at the cervical region and thereby contributing to the formation of an NCCL. This type of tooth tissue loss at the CEJ was termed "abfraction" by Grippo[5] in 1991 to distinguish it from erosion and abrasion. It was reported that abfraction occurs frequently in teeth with wear facets and that the occurrence ratio is high in bruxists as well.[4, 15, 16] Burke et al[1] supported the tooth flexure theory of cervical tooth tissue loss based on a focus that the lesions occur in teeth subjected to lateral force but not in adjacent teeth if they were not subjected to lateral forces, and the lesions may be subgingival which do not receive the effect of erosion and abrasion.

To observe the stress distribution patterns within the tooth due to occlusal loading and to prove the mechanism of abfraction, various types of stress and strain analyses including strain gauge studies,[2, 17, 18] photoelastic stress analysis,[18-20] and finite element analysis[2, 21-27] had been carried out previously.

After finite element analysis used in dentistry by Farah[28], it was often applied to investigate stress distribution in a normal tooth since it can readily cope with both the complex geometry of a tooth and its surrounding structures with a large variation in physical properties of the enamel, dentin, periodontal ligament, cortical bone, and cancellous bone.[2, 21, 23, 25]

However, until now, the finite element analysis has been accomplished with those procedures; the modeling of a tooth and its surrounding structure has been achieved by taking data from an anatomic atlas, sectioning of the specimen, and manually tracing of photographs.[2, 21, 23, 27, 29] A modeling of the surrounding bone that is thought to affect tooth stress distribution was omitted, or surrounding bone was modeled as a simplified homogeneous substance excluding microarchitecture of trabecular bone because the capability to determine the trabecular bone pattern was not available.[30] The finite element analyses by those methods have many limitations to revealing the accurate aspect of stress distribution within the tooth. The cancellous bone, which supports the tooth, is composed of complicated and minute trabecular bone structure and has variation in structure and bone quality with individual, sex, and age.[31, 32] As the functional forces are placed on a tooth, the surrounding bone can adapt to the stresses and increase its density.[33, 34] The process of alveolar bone remodeling can change the stress distribution pattern in a tooth and deteriorate the abfraction lesions. Consequently, the stress distribution pattern in tooth was considered to be different with depending on the bone quality of the trabecular bone. However, up to now, researches have not considered the difference with respect to the trabecular bone quality and could not technically be able to reflect microarchitecture of cancellous bone on the finite element model.

Micro-computed tomography (micro-CT) was initially introduced in the field of bone biology by Layton et al.[35] and Feldkamp et al.[36] The new digital imaging tool was facilitated to get trabecular bone image with high resolution of micron unit. The micro-CT is reported to be able to get the three dimensional (3D) image of the bone with a non-invasive method and that it has a high interrelationship with the histology of real bone biopsy[37-40]. The micro-Finite Element (micro-FE) Analysis which stands on micro-CT was recently developed and widely used to research the biomechanical properties of trabecular bone[41-43].

The aim of this study is to produce two dimensional (2D) micro-FE models using a micro-CT that reflect the microarchitecture of the tooth and supporting structure and to observe the stress distribution in human premolar region related to the supporting bone quality. The hypothesis used in this study was that there would be no differences in the stress distribution related to the supporting bone quality.

II. MATERIALS AND METHODS

1. Sample preparation and micro-CT scanning

A mandibular bone including a lower first premolar was sectioned bucco-lingually with thickness of 10 mm from a dissection cadaver using a diamond saw (Isomet, Buehler Co., Lake Bluff, Illinois, U.S.A). The specimen was fixated with 10% buffered formalin solution and dehydrated in 70% alcohol solution.

The specimen was scanned with a micro-CT (Skyscan-1072, SKYSCAN, Antwerpen, Belgium) in about 2,000 horizontal slices. A scan grid of 1024 X 1024 was selected with a pixel size of 21.3㎛ X 21.3㎛. The crown portion of premolar was scanned separately as the height of the specimen was larger than the field of view (FOV) during micro-CT scanning.

Fig 1. The micro-CT image of the mandibular specimen used in this study.

2. Generation of the 2D micro-FE models

The scan data were reconstructed into 3D image with a voxel size of 21.3㎛ X 21.3㎛ X 21.3㎛ using the computer program (BIONIX software package, CANTIBio. Inc, Kyonggi, Korea). A longitudinal 2D image of the central bucco-lingual section of a lower premolar and surrounding structures was taken from the 3D image (Figure 1). A 2D micro-FE model was produced from the 2D image of a premolar and surrounding structures using Altair® HyperMesh® 5.0(Altair Engineering, Michigan, USA).

The pilot study was conducted to produce the 2D micro-FE model which resembles more real situation.[44] The following results were observed. First, the pulp in 2D FE model intercepts the stress inside a tooth and 2D model including the pulp showed different stress distribution pattern. So, the dental pulp must be removed when using 2D FE model. However, in 3D FE model, the existence of the pulp did not influence stress distribution pattern within the tooth[45, 46]. Second, the enamel must be modeled as an anisotrophic material. This is in agreement with results of previous researches[24, 47]. Based on results of the above pilot study, an experiment was executed using a model which gives the anisotrophism in the enamel after removing pulp from the tooth.

Because the buccal bone of the used specimen had severe alveolar bone resorption, the cortical bone was added on defective buccal bone area by computational manipulation and this model was used as the base model.

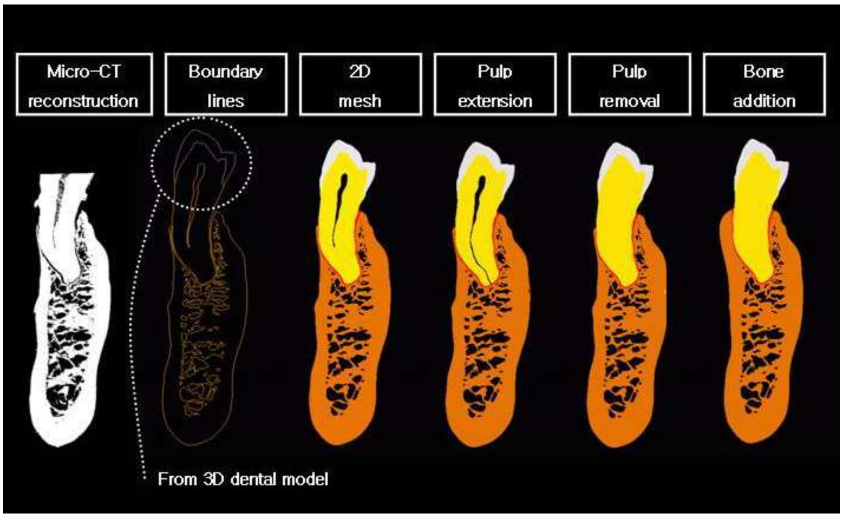

Fig 2. Modeling process.

Replacing cancellous bone with cortical bone in the base model (intermediate bone model), a dense bone model was produced, and by reducing 30% of cancellous bone pattern from base model, a loose bone model was produced. Finally, three models of different bone quality (dense, intermediate, and loose bone quality) were produced with change of structure and density of cancellous bone.

3. Loading conditions and 2D micro-FE analysis

A vertical load of 100N and a horizontal load of 100N were applied to the buccal cusp region of a lower first premolar as shown in Fig 3. and the 100N forces were equally divided into 4 point forces of 25N and applied onto 4 nodes of buccal cusp tip region. The stress distribution patterns within a tooth were analyzed with each model using MSC.Nastran FEM Package (MSC Software®, Santa Ana, CA, USA). For the boundary conditions, the inferior border of mandible was rigidly fixed in x and y directions so not to move when subjected to force systems. In pilot study, when compared to the situation that the middle portion of mandible was fixed, there was little difference in stress distribution. The physical properties of the materials used in this study were given in Table 1. [48]

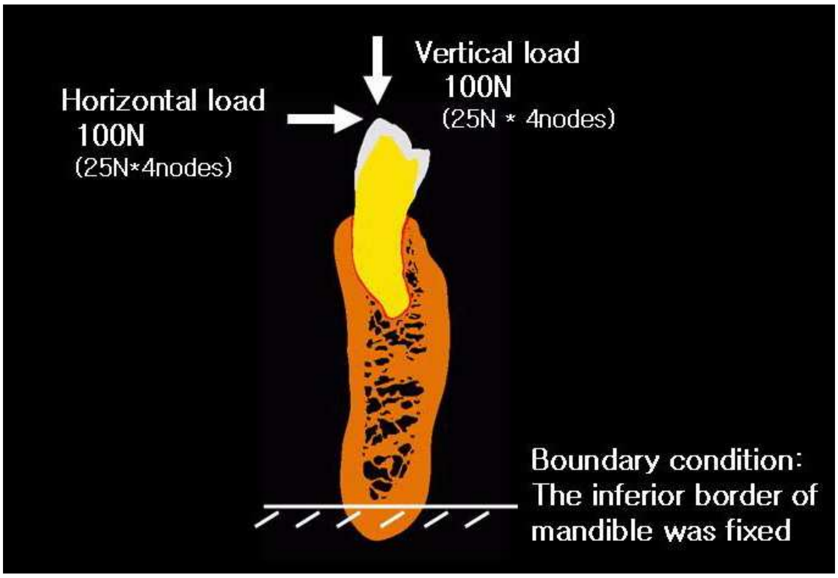

Fig 3. Loading and boundary condition.

Table 1. Physical properties of the tooth and supporting bone used in this study

Material	E(MPa)	ν
Enamel (Ex)	80,000	0.30
Enamel(Ey)	20,000	0.30
Dentin	15,000	0.31
Cortical bone	13,800	0.26
Cancellous bone	345	0.31
Periodontal ligament	50	0.49

III. RESULTS

2D micro-FE models that reflect the microarchetecture of a premolar and supporting structure could be generated in this study (Fig 4.). A complicated trabecular pattern of cancellous bone could be recreated in great detail according to the cross-sectional image of micro-CT in each model.

When the load was applied on the buccal cusp of the models, the stress distribution patterns are given in Fig 5. Inside the tooth, the stress was mostly concentrated on buccal cervical portion between CEJ area and cervical root area which meets with buccal alveolar bone crest and three models showed similar stress distribution patterns.

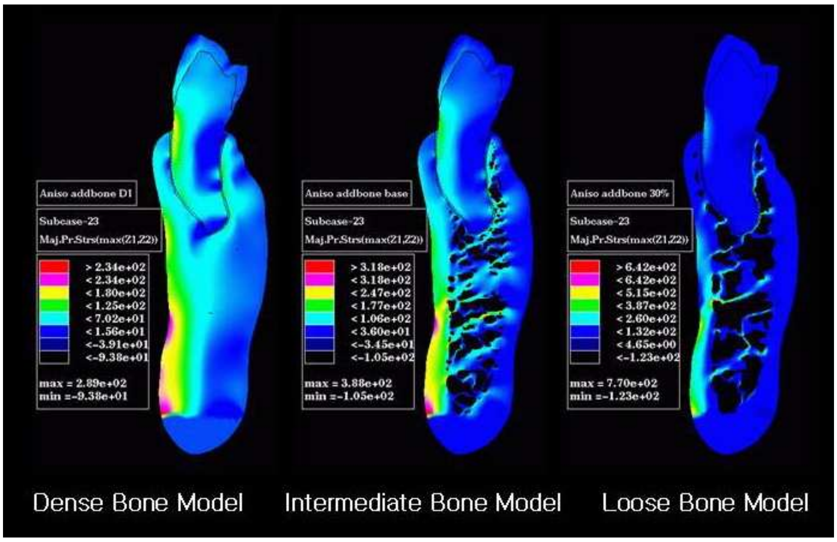

Fig 4. Stress distribution patterens within a tooth and supporting bone.

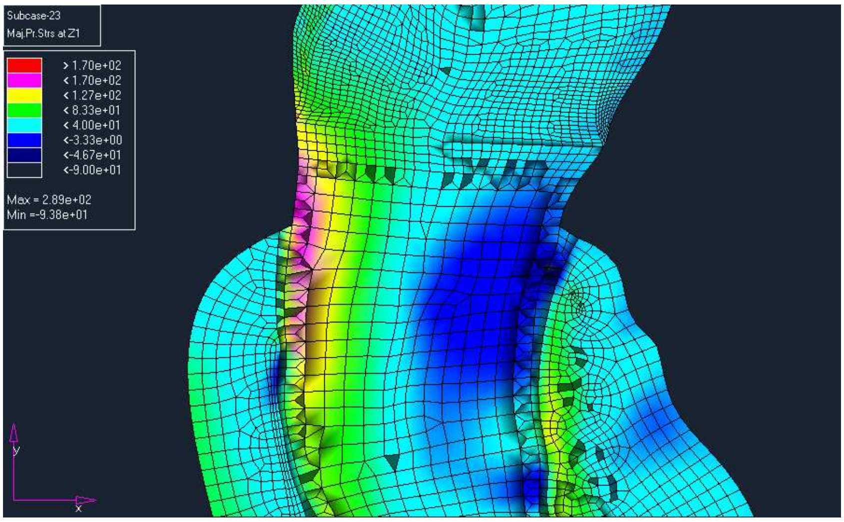

Fig 5. Stress distribution pattern in dense bone model.

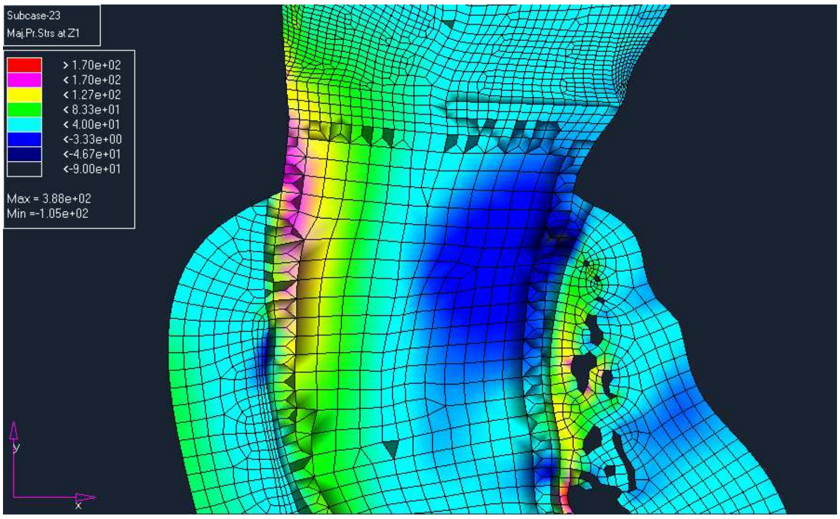

Fig 6. Stress distribution pattern in intermediate bone model.

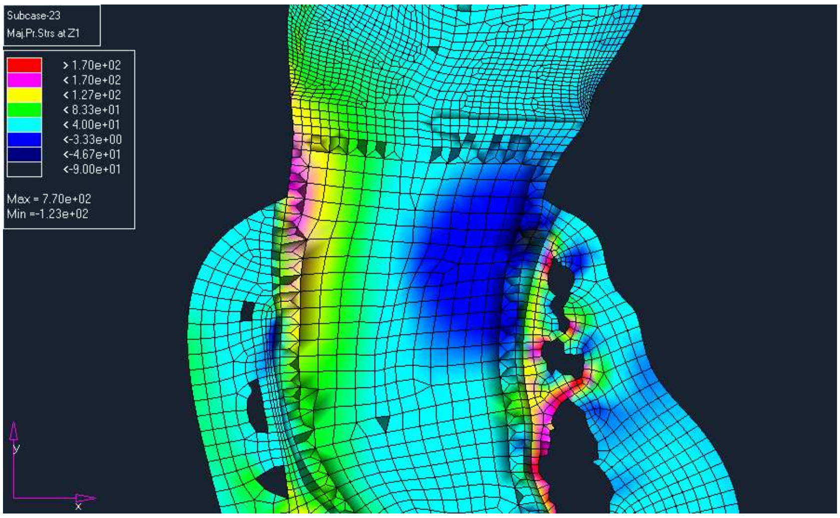

Fig 7. Stress distribution pattern in loose bone model.

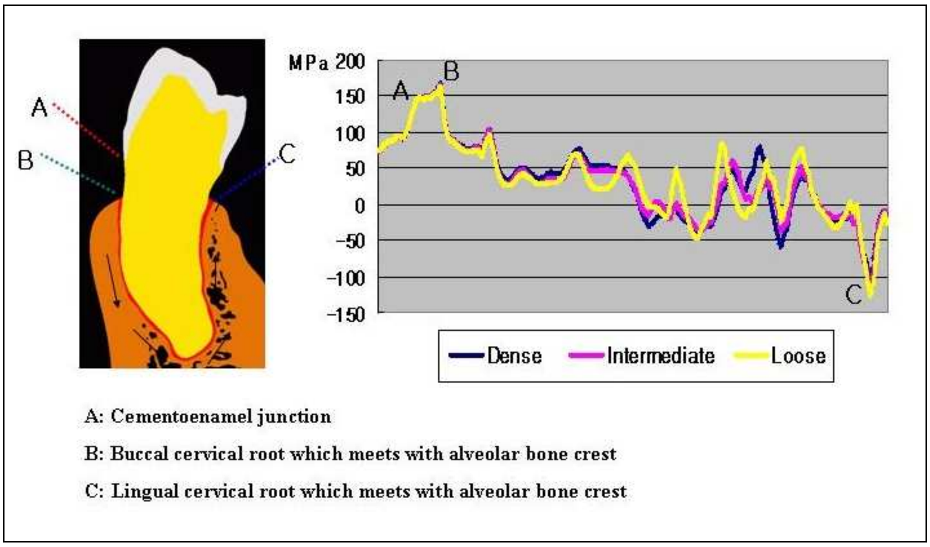

Fig 8. Graph of calculated stresses along the tooth surface.

Fig 8 shows stress level which was measured along the tooth surface in three models. On the buccal cervical area, between CEJ area (A point) to cervical root area justaposed to buccal alveolar bone crest (B point), a highest stress value of greater than 150MPa was developed. Although dense bone model showed slightly higher peak stress value on the buccal cervical area than the others, there was little difference in three bone models.

Other than the buccal cervical portion, irregular pattern of stress distribution was shown depending on the bone density of the contacting bone and the stress values were much less than the stress level found at the buccal cervical area.

IV. DISCUSSION

When occlusal forces are exerted on a tooth during mastication and parafunction, flexure of the tooth can occur. The tensile force generated by tooth flexure can cause disruption of the bonds between enamel hydroxyapatite crystals near CEJ, resulting in cracks in the enamel and, finally, loss of affected enamel and underlying dentine in that region. This tooth flexure theory has been accepted as the mechanism of abfraction.[1, 3, 4, 13, 18, 49]

Many investigators have accomplished various FE analyses in tooth models and have demonstrated that the tensile stress due to occlusal loading concentrates on the cervical region of the tooth, thereby leading to abfraction.[2, 23, 26] These FE analyses can be influenced by loading condition,[26] material properties such as enamel anisotrophism[24, 47] and boundary condition and those modeling conditions may affect stress distribution pattern. Rees[27] suggested that when examming stresses within the cervical region of the tooth it is important to model all the supporting structures and revealed the great difference of stress distribution when removing or including the periodontal ligament and alveolar bone. Therefore, it is very valuable to model the periodontal ligament and alveolar bone. Alveolar bone is composed of cortical bone and cancellous bone. The cortical bone is composed of compact bone which is dense in nature and provides strength and protection and is easy to model because of its simple geometry. On the contrary, cancellous bone, a spongy, porous type of bone tissue made of rods and/or plates, has a complex trabecular pattern and has large variations of bone quality in individual more than cortical bone. Such variation of cancellous bone quality is thought to play an important role in load transmission within a tooth during occlusal loading, but previous study examined the stress distribution without consideration of trabecular pattern of cancellous bone.

Micro-CT is a powerful digital imaging tool which especially creates 3D images of complex geometry in bone while it was impossible in conventional CT with a resolution power of several millimeters.[30, 50] A complex 3D microstructure of cancellous bone can be acquired in great detail by high resolution imaging techniques such micro-CT.

Micro-FE modeling together with high resolution imaging techniques such as micro-CT, peripheral qualitative computed tomography (pQCT), and micro-magnetic resonance imaging (micro-MRI) technique has been used extensively used to study the mechanical properties of trabecullar bone.[41, 51] The main disadvantage of this approach is its huge computational requirements because of the enormous increase in element number and it is difficult to accomplish time-consuming tedious work. Thanks to the recent developed computer system and improvement of software package and algorithms that automatically creates mesh, the modeling process becomes simplified and calculation time in a laboratory is gradually shortened.[52, 53] In this study, it was able to produce the micro-FE model that can represent the microarchitecture of a tooth and supporting bone. Based on base model (intermediate bone model), another two models of dense and loose bone quality were produced by simple computational manipulation. Finally, three 2D micro-FE models were generated of the central bucco-lingual section of a lower first premolar and supporting structures and the stress distribution pattern in the tooth was analyzed.

It was found that the stress was mostly concentrated on the buccal cervical area, in agreement with the previous studies.[2, 21, 23] When the occlusal forces are loaded on the tooth, the fulcrum against loading direction is almost located on the crest of the alveolar bone and on the tooth this is near the root cervical CEJ area.[54] A significant force acting on a tooth at the fulcrum would create tension on one side and compression on the opposing side of equal magnitude.[55] This may be the reason why abfraction lesions occur on the cervical CEJ area. Histologically, because the normal scalloping pattern of enamel and dentin is insufficient at the dentino-enamel junction of cervical portion, mechanical bonding of the enamel and the dentin is weaker than other area.[56] Besides its mechanical bonding in cervical portion being weak, cervical enamel was structurally weaker because it had less mineral content, poorer structure, and 30% less compressive strength than cuspal enamel.[57, 58] The occlusal stress that assaults the functional cusp propagates in the enamel and generates high stress at CEJ region. This high stress destroys the cervical enamel crystal that has histologically weaker structure compared to cusp enamel and the abfraction lesion initiated. If the enamel at the CEJ region had broken away, the underlying dentin is exposed to external environment and the abfraction lesion becomes worse by acidic erosion, tooth brushing abrasion, and caries due to food retention. Kuroe T. et al[19] pointed that the presence of a cervical lesion changed occlusal load-induced stress distribution and it deteriorated the abfracsive lesions more seriously.

Also, high stress level was found at cervical root portion that meet buccal alveolar bone crest. The cervical tooth substance loss at this portion is hardly shown clinically. This can be explained by the following reasons: First, this portion is mainly composed of dentin that have somehow low elastic modulus value (elastic modulus of dentin is 1,500MPa), and it can absorb some degrees of stress compared to enamel that is more brittle (Elastic modulus of Enamel is 8,000MPa(Ex) and 2,000MPa(Ey)). Second, because this region was surrounded by periodontium and was isolated from external environment, it was freed from the effect of erosion and abrasion that deteriorates the abfracsive lesion. Although the very heavy concentration of stress was observed in that region, the cervical tooth loss does not happen clinically.

There was no difference in stress distribution pattern related to different cancellous bone quality although there was a slightly higher stress peak value on the buccal cervical area in dense bone model than loose bone model. The bone quality of cancellous bone, which occupy large portion of tooth supporting bone, was thought to have great influence on load transmission within a tooth, but it did not have influence on stress distribution. Normally, tooth does not contact the alveolar bone directly; a tooth is suspended in its socket by the fibers of the periodontal ligament that is a thin, fibrous ligament that connects tooth to surrounding alveolar bone. Those fibers act as shock absorbers to cushion the force of the mastication. Therefore, the stresses, transmitted through tooth, are absorbed in some degree in the periodontal ligament space. The periodontal ligament has an important role in the masticatoy force system. The alveolar bone includes the cortical bone, the trabecular bone, and the alveolar bone proper. The alveolar bone proper is a thin layer of compact bone that is a specialized continuation of cortical plate and forms the alveolar socket. The occlusal stress, passing through the periodontal ligament space, is propagated to alveolar bone proper which is connected mainly to cortical plate. Consequently, the occlusal stress is transmitted to cortical plate by alveolar bone proper and the cancellous bone has little influence on stress distribution.

Various factors associated with abfraction lesion should be considered. These include load direction and number of occlusal contact, physical properties of dentin and enamel, tooth morphology, clinical crown length, individual variation, age, crown root ratio, root configuration, arch alignment of the tooth, periodontal support, and supporting bone quality and the abfraction lesion occur in a variety of forms depending in those factors. Moreover, NCCLs including abfraction are not result of single dominant etiologic factor and a number of authors supported a multifactorial concept in NCCLs and advocated using the term “noncarious cervical lesion” since “abrasion”, “erosions”, or “abfraction” implies a single etiology.[59, 60]

In this study, it was possible to acquire the microarchitecture of the tooth and supporting bone accurately using micro-CT, to produce 2-D micro-FE models based on digital image from micro-CT, and to allow more accurate interpretation of the stress distribution pattern in a tooth than previously available methods. Moreover, it was able to reveal the interrelationship of abfraction and stress distribution in tooth and to examine the stress distribution pattern related to supporting bone quality.

V. CONCLUSION

The 2D micro-FE model of the lower first premolar and supporting bone was generated and the stress distribution pattern related to different bone quality was investigated. The following conclusion could be drawn:

1. It was able to obtain the digital images of microarchitecture of tooth and supporting bone accurately using micro-CT and to generate 2D micro-FE model based on this digital image more easily.
2. It was possible to interpret the stress distribution in a tooth more accurately than previous method by reflecting the microarchitecture of cancellous bone and proper physical properties of the tooth and supporting bone on model,
3. The stress mostly concentrated on tooth cervical portion, between CEJ area to cervical root area which meets with buccal alveolar bone crest.
4. There was no difference in stress distribution pattern related to supporting bone quality although there was a slightly higher stress peak value on the buccal cervical area in dense bone model than loose bone model .

REFERENCES

1. Burke FJ, Whitehead SA, McCaughey AD. Contemporary concepts in the pathogenesis of the Class V non-carious lesion. Dental Update 1995;22(1):28-32.
2. Palamara D. Strain patterns in cervical enamel of teeth subjected to occlusal loading. Dental Materials 2000;16(6):412-9.
3. Levitch LC, Bader JD, Shugars DA, Heymann HO. Non-carious cervical lesions. Journal of Dentistry 1994;22(4):195-207.
4. Lee WC, Eakle WS. Possible role of tensile stress in the etiology of cervical erosive lesions of teeth. Journal of Prosthetic Dentistry 1984;52(3):374-80.
5. Grippo JO. Abfractions: a new classification of hard tissue lesions of teeth. Journal of Esthetic Dentistry 1991;3(1):14-9.
6. Rees JS. A review of the biomechanics of abfraction. European Journal of Prosthodontics and Restorative Dentistry 2000;8(4):139-44.
7. Donachie MA, Walls AW. Assessment of tooth wear in an ageing population. Journal of Dentistry 1995;23(3):157-64.
8. Coleman TA, Grippo JO, Kinderknecht KE. Cervical dentin hypersensitivity. Part II: Associations with abfractive lesions. Quintessence International 2000;31(7):466-73.
9. Gallien GS, Kaplan I, Owens BM. A review of noncarious dental cervical lesions. Compendium of Continuing Education in Dentistry 1994;15(11):1366, 68-72, 74; quiz 74.

10. Gilmore AG, Beckett HA. The voluntary reflux phenomenon. British Dental Journal 1993;175:368-72.
11. Kelleher M, Bishop K. The aetiology and clinical appearance of tooth wear. European Journal of Prosthodontics and Restorative Dentistry 1997;5(4):157-60.
12. Bishop K, Kelleher M, Briggs P, Joshi R. Wear now? An update on the etiology of tooth wear. Quintessence International 1997;28(5):305-13.
13. McCoy G. The etiology of gingival erosion. Journal of Oral Implantology 1982;10(3):361-2.
14. Lehman ML, Meyer ML. Relationship of dental caries and stress: concentrations in teeth as revealed by photoelastic tests. Journal of Dental Research 1966;45(6):1706-14.
15. Kim HJ, Chung MK. The effect of occlusal stress on cervical abfraction. The Journal of Korean Academy of Prothodontics 1996;34(2):299-308.
16. Xhonga FA. Bruxism and its effect on the teeth. Journal of Oral Rehabilitation 1977;4(1):65-76.
17. Nohl FS, Setchell DJ. Surface strains induced by measured loads on teeth in vivo: a methodological study. European Journal of Prosthodontics and Restorative Dentistry 2000;8:27-31.
18. Asundi A, Kishen A. A strain gauge and photoelastic analysis of in vivo strain and in vitro stress distribution in human dental supporting structures. Archives of Oral Biology 2000;45(7):543-50.
19. Kuroe T, Itoh H, Caputo AA, Konuma M. Biomechanics of cervical tooth structure lesions and their restoration. Quintessence International

2000;31(4):267-74.

20. Kuroe T, Itoh H, Caputo AA, Nakahara H. Potential for load-induced cervical stress concentration as a function of periodontal support. Journal of Esthetic Dentistry 1999;11(4):215-22.

21. Goel VK, Khera SC, Ralston JL, Chang KH. Stresses at the dentinoenamel junction of human teeth--a finite element investigation. [see comments]. Journal of Prosthetic Dentistry 1991;66(4):451-9.

22. Goel VK, Khera SC, Singh K. Clinical implications of the response of enamel and dentin to masticatory loads. Journal of Prosthetic Dentistry 1990;64(4):446-54.

23. Khera SC, Goel VK, Chen RC, Gurusami SA. A three-dimensional finite element model. Operative Dentistry 1988;13(3):128-37.

24. Spears IR. A three-dimensional finite element model of prismatic enamel: a re-appraisal of the data on the Young's modulus of enamel. Journal of Dental Research 1997;76(10):1690-7.

25. Rees JS. The role of cuspal flexure in the development of abfraction lesions: a finite element study. European Journal of Oral Sciences 1998;106(6):1028-32.

26. Rees JS. The effect of variation in occlusal loading on the development of abfraction lesions: a finite element study. Journal of Oral Rehabilitation 2002;29:188-93.

27. Rees JS. An investigation into the importance of the periodontal ligament and alveolar bone as supporting structures in finite element studies. Journal of Oral Rehabilitation 2001;28(5):425-32.

28. Farah JW, Craig RG, Sikarskie DL. Photoelastic and finite element stress analysis of a restored axisymmetric first molar. Journal of Biomechanics 1973;6(5):511-20.

29. Tanaka A, Naito T, Yokota M, Kohno M. Finite element analysis of the possible mechanism of cervical lsion formation by occlusal force. Journal of Oral Rehabilitation 2003;30:60-67.

30. Verdonschot N, Fennis WM, Kuijs RH, Stolk J, Kreulen CM, Creugers NH. Generation of 3-D finite element models of restored human teeth using micro-CT techniques. International Journal of Prosthodontics 2001;14(4):310-5.

31. Parfitt GJ. An investigation of the normal variations in alveolar bone trabeculation. Oral Surgery, Oral Medicine, and Oral Pathology 1962;15:1453-63.

32. von_Wowern N. Variations in structure within the trabecular bone of the mandible. Scandinavian Journal of Dental Research 1977;85(7):613-22.

33. Ramfjord SP, Kohler CA. Periodontal reaction to functional occlusal stress. Journal of Periodontology 1959;30:95-112.

34. Hallmon WW. Occlusal trauma: Effect and impact on the periodontium. Annals of Periodontology 1999;4:102-07.

35. Layton MW, Goldstein SA, Goulet RW, Feldkamp LA, Kubinski DJ, Bole GG. Examination of subchondral bone architecture in experimental osteoarthritis by microscopic computed axial tomography. Arthritis and Rheumatism 1988;31:1400-05.

36. Feldkamp LA, Goldstein SA, Parfitt AM, Jesion G, Kleerekoper M. The

direct examination of three-dimensional bone architecture in vitro by computed tomography. Journal of Bone and Mineral Research 1989;4(1):3-11.

37. Uchiyama T, Tanizawa T, Muramatsu H, Endo N, Takahashi HE, Hara T. A morphometric comparison of trabecular structure of human ilium between microcomputed tomography and conventional histomorphometry. Calcified Tissue International 1997;61(6):493-8.

38. Muller R, Hahn M, Vogel M, Delling G, Ruegsegger P. Morphometric analysis of noninvasively assessed bone biopsies: comparison of high-resolution computed tomography and histologic sections. Bone 1996;18(3):215-20.

39. Muller R, Van_Campenhout H, Van_Damme B, Van_Der_Perre G, Dequeker J, Hildebrand T, et al. Morphometric analysis of human bone biopsies: a quantitative structural comparison of histological sections and micro-computed tomography. Bone 1998;23(1):59-66.

40. Stoppie N, van der Waerden JP, Jansen JA, Duyck J, Wevers M, Naert IE. Validation of microfocus computed tomography in the evaluation of bone implant specimens. Clinical Implant Dentistry and Related Research 2005;7(2):87-94.

41. van_Rietbergen B. Micro-FE analyses of bone: state of the art. Advances in Experimental Medicine and Biology 2001;496:21-30.

42. van_Rietbergen B, Majumdar S, Pistoia W, Newitt DC, Kothari M, Laib A, et al. Assessment of cancellous bone mechanical properties from micro-FE models based on micro-CT, pQCT and MR images. Technology and Health

Care : Official Journal of the European Society For Engineering and Medicine 1998;6(5-6):413-20.

43. Guldberg RE, Hollister SJ, Charras GT. The accuracy of digital image-based finite element models. Journal of Biomechanical Engineering 1998;120(2):289-95.

44. Suh YJ, Shim J, S,, Lee KW, Chung MK, Lee HJ. The effect of varying peripheral bone structure and bone density on the occlusal stress distribution of human premolar regions. The Journal of Korean Academy of Stomatognathic Function and Occlusion 2003;19(1):7-15.

45. Rubin C, Krishnamurthy N, Capilouto E, Yi H. Stress analysis of the human tooth using a three-dimensional finite element model. Journal of Dental Research 1983;62(2):82-6.

46. Hojjatie B, Anusavice KJ. Three-dimensional finite element analysis of glass-ceramic dental crowns. Journal of Biomechanics 1990;23(11):1157-66.

47. Rees JS, Jacobsen PH. Modelling the effects of enamel anisotropy with the finite element method. Journal of Oral Rehabilitation 1995;22(6):451-4.

48. Rees JS, Jacobsen PH. Elastic modulus of the periodontal ligament. Biomaterials 1997;18(14):995-9.

49. Hattab FN, Yassin OM. Etiology and diagnosis of tooth wear: a literature review and presentation of selected cases. The International Journal of Prosthodontics 2000;13(2):101-7.

50. Rebaudi A, Koller B, Laib A, Trisi P. Microcomputed tomographic analysis of the peri-implant bone. The International Journal of Periodontics & Restorative Dentistry 2004;24:316-25.

51. Borah B, Gross GJ, Dufresne TE, Smith TS, Cockman MD, Chmielewski PA, et al. Three-dimensional microimaging (MRmicroI and microCT), finite element modeling, and rapid prototyping provide unique insights into bone architecture in osteoporosis. Anatomical Record 2001;265(2):101-10.

52. Cattaneo PM, Dalstra M, Frich LH. A Three-dimensional finite element model from computed tomography data: a semi-automated method. Proceeding of the Institution of Mechical Engineers. Part H, Journal of engineering in medicine 2001;215:203-13.

53. Sato Y, Teixeira ER, Tsuga K, Shindoi N. The effectiveness of a new algorithm on a three-dimensional finite element model construction of bone trabeculae in implant biomechanics. Journal of Oral Rehabilitation 1999;26(8):640-3.

54. Lee HE, Lin CL, Wang CH, Cheng CH, Chang CH. Stresses at the cervical lesion of maxillary premolar--a finite element investigation. J Dent 2002;30(7-8):283-90.

55. Lee WC, Eakle WS. Stress-induced cervical lesions: review of advances in the past 10 years. Journal of Prosthetic Dentistry 1996;75(5):487-94.

56. Spir A. Surface characteristics of human enamel and dentin: a SEM study[Matster's thesis]. Iowa City: University of Iowa Graduate College 1988.

57. Poole DFG, Newman HN, Dibdin GH. Structure and porosity of human cervical enamel studied by polarizing microscopy and transmission electron microscopy. Archives of Oral Biology 1981;26:977-82.

58. Stanford JW, Paffenbarger GC, Kampula JW. Determination of some

compressive properties of human enamel and dentine. Journal of the American Dental Association 1958;57:487.

59. Litonjua LA, Andreana S, Bush PJ, Tobias TS, Cohen RE. Noncarious cervical lesions and abfractions: a re-evaluation. Journal of the American Dental Association 2003;134(7):845-50.

60. Mayhew RB, Jessee SA, Martin RE. Association of occlusal, periodontal, and dietary factors with the presence of non-carious cervical dental lesions. Am J Dent 1998;11(1):29-32.

국문요약

지지골의 골질에 따른 사람 하악 소구치에서의 응력분포 : 미세 컴퓨터 단층 촬영을 이용한 유한요소분석

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교합압에 의한 치아내 응력 분포 양상을 조사하고, 교합압과 굴곡파절의 연관성을 밝히고자 많은 생역학적 연구가 진행되어 왔다. 그러나, 이러한 연구들은 치아내 응력 분포에 큰 영향을 끼치리라 생각되는 치아 주위 지지골의 미세구조를 고려하지 않고 진행되어 왔다. 이 연구의 목적은 치아와 지지골의 미세구조가 반영된 2차원 미세 유한요소 모델을 제작하고 지지골의 골질에 따른 치아내 응력분포 양상을 조사하는 것이다.

하악 제1소구치를 포함하는 사람 하악골 표본을 대상으로 미세컴퓨터단층촬영을 시행하여 단층 촬영상을 얻었다. 이 단층상을 이용해서 세가지 골질의 지지골과 치아의 2차원 미세유한요소 모델 (dense, intermediate, and loose bone model)을 제작하고, 각 모델의 소구치 협측 교두정에 각각 100N의 수직력과 수평력를 가해 치아내 응력분포를 조사하였다.

응력의 대부분은 협측 치경부에 집중되었으며, 골질에 따른 세가지 모델에서 응력분포의 차이점은 없었고, 골질이 우수한 dense bone model이 다른 모델에 비해 응력이 다소 높게 집중되고 있었다.

본 실험에서는 미세 컴퓨터 단층 촬영으로 얻어진 디지털 영상을 기반으로 치아 및 지지골의 미세구조가 반영된 2차원 미세 유한요소 모델의 제작이 가능하여 치아내 응력분포 양상에 관한 해석의 정확성을 높힐 수 있었다.

핵심되는 말: 응력 분포, 치아, 지지골, 비우식성 치경부 병소, 굴곡파절, 미세 컴퓨터 단층 촬영, 유한요소 분석.