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Influence of different modeling strategies for the periodontal ligament on finite element simulation results

Ansgar Hohmann,[a] Cornelia Kober,[b] Philippe Young,[c] Christina Dorow,[a] Martin Geiger,[a] Andrew Boryor,[a] Franz Martin Sander,[a] Christian Sander,[a] and Franz Günter Sander[d]
Ulm and Hamburg, Germany, and Exeter, United Kingdom

Introduction: The finite element method is a promising tool to investigate the material properties and the structural response of the periodontal ligament (PDL). To obtain realistic and reproducible results during finite element simulations of the PDL, suitable bio-fidelic finite element meshes of the geometry are essential. **Methods:** In this study, 4 independent coworkers generated altogether 17 volume meshes (3-dimensional) based on the same high-resolution computed-tomography image data set of a tooth obtained in vivo to compare the influence of the different model generation techniques on the predicted response to loading for low orthodontic forces. **Results:** It was shown that the thickness of the PDL has a significant effect on initial tooth mobility but only a remarkably moderate effect on the observed stress distribution in the PDL. Both the tooth and the bone can be considered effectively rigid when exploring the response of the PDL under low loads. The effect of geometric nonlinearities could be neglected for the applied force system. **Conclusions:** Most importantly, this study highlights the sensitivity of the finite element simulation results for accurate geometric reconstruction of the PDL. (Am J Orthod Dentofacial Orthop 2011;139:775-83)

The biomechanical background of orthodontic tooth movement has been explored by many authors.[1-8] The periodontal ligament (PDL) is part of the periodontium. This periodontium additionally comprises the alveolar bone, the dental cementum, and the gingiva, and it supports the teeth and maintains them in the maxillary and mandibular bones. The PDL is a thin connective tissue connecting the tooth root with the surrounding alveolar bone (Fig 1, *A*). Because of its low stiffness (Table I), the PDL plays a key role in tooth mobility.[1,9] It is widely acknowledged that orthodontic tooth movement principally depends on stress or strain in the PDL.

Characterization of the PDL by using standard mechanical testing is not trivial because of the complexity of isolating and preserving a sample of appropriate dimensions for testing. An alternative approach is to use experimental measurements of whole tooth movement combined with simulations on subject-specific image-based finite element models to infer the material properties. This is effectively using the finite element method to study the inverse problem: with at least 1 measured displacement of the tooth under prescribed loads, what are the material properties of the PDL in the finite element model that would replicate the experimentally observed response of the system? Of course, the effectiveness of this approach is contingent on obtaining suitably accurate finite element models of the tooth and the periodontium being experimentally tested. Further difficulties could occur because of the nonhomogeneity of the tissues.

In animal or human in-vitro studies, it is possible to generate accurate finite element models of a tooth and periodontium because methods such as microcomputed tomography or serial sectioning of the samples can be used.[2,10] This is more difficult in human in-vivo studies. In addition to approximating the PDL by well-known geometric shapes or average literature values as parabolas,[6,7,11-13] finite element models were generated starting from radiologic data subjected to the limitations of the respective imaging accuracy.[1,2,8,9,14,15] Most authors generated the PDL with a constant

[a]Research scientist, Department of Orthodontics, University of Ulm, Ulm, Germany.
[b]Professor, Faculty of Life Sciences, Hamburg University of Applied Sciences, Hamburg, Germany.
[c]Professor, School of Engineering, Computer Science and Mathematics, University of Exeter, Exeter, United Kingdom.
[d]Professor and head, Department of Orthodontics, University of Ulm, Ulm, Germany.

Philippe Young has a financial interest in Simpleware, Exeter, United Kingdom.

Reprint requests to: Ansgar Hohmann, Universitätsklinikum Ulm, Department of Orthodontics, ZMK 4, Albert-Einstein-Allee 11, 89081 Ulm, Germany; e-mail, ansgar.hohmann@uni-ulm.de.

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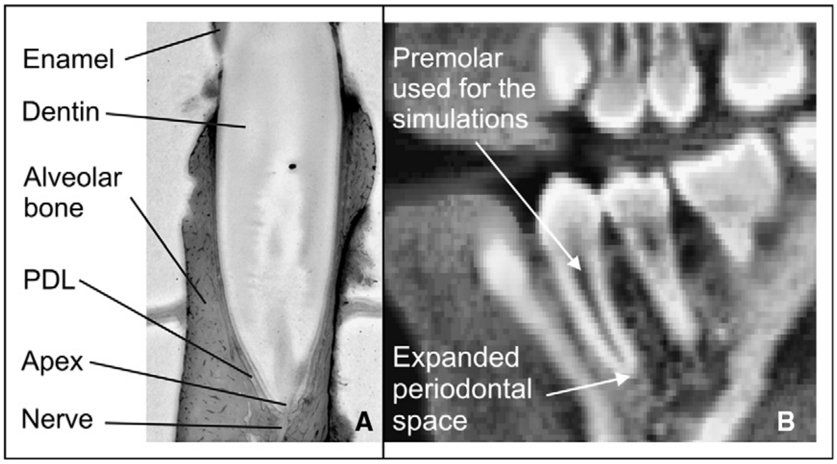

Fig 1. A, Dental anatomy; **B,** sagittal view of the CT data set used for model generation.

thickness.[1,6,8,9,12,13] Either hexahedral or tetrahedral element meshes were used by all authors.[1,2,6-15]

The process of going from image to mesh involves a number of processing steps, each with its own potential for introducing further geometric errors. Aspects such as the influence of volume-preserving smoothing on the segmented PDL image, which will be shown to have a significant impact on the accuracy of simulation results in this article, have not previously been investigated.

This study was principally aimed at comparing 4 strategies for image-based model generation of the PDL on the finite element simulation results and, thereby, to assess the sensitivity of simulation results to modeling assumptions during segmentation and meshing. Furthermore, validation of the applied boundary conditions (bone as stiff material for low orthodontic forces) will be provided. To this end, 4 independent strategies were used to generate finite element models based on identical image data of a tooth. To our knowledge, there is no comparable study in the literature investigating the effect of different geometric modeling approaches chosen by different researchers on simulation results.

MATERIAL AND METHODS

Finite element mesh generation of a premolar from a patient was performed according to 4 independent strategies by 4 independent researchers (C.D., P.Y., A.H., C.K.). Altogether, 17 finite element meshes of this premolar were generated.

Two strategies (1 and 3) were based on approximating early on the geometry of the PDL (by using prescribed thicknesses), whereas strategies 2 and 4 were entirely image based.

All finite element models generated in this study refer to a mandibular first premolar from clinically indicated

Table I. Parameters for the mechanical properties of dentin, PDL, and cortical and cancellous bone used for the modified calculations[1,9]

	Elastic modulus (MPa)	*Poisson's ratio*
PDL	0.1	0.45
Dentin	18600	0.3
Cortical bone	1000	0.3
Cancellous bone	500	0.3

CT data (acquired with a MxTwin CT device, Picker, Cleveland, Ohio; z-distance, 0.6 mm; pixel size, 0.352 $\times$ 0.352 mm^2) of a 14-year-old boy (Fig 1, *B*). The data were processed with AMIRA software (version 4.0, Mercury Computer Systems, Berlin, Germany). At the apex of the tooth, an increased periodontal space was observed, probably a sign of a not-yet completely formed premolar.

For strategy 1, the first coworker (C.D.) used the method described by Clement et al,[14] Dorow and Sander,[9] and Dorow.[1] Segmentation, model generation, and preprocessing for finite element analysis for the first model were performed by using the visualization toolbox AMIRA[16,17] and finite element software (ANSYS, Canonsburg, Pa). Mapped meshes of 8-noded hexahedral elements with 3 elements across the thickness of the PDL were generated to create 3 models with different prescribed constant thicknesses (measured perpendicular to the tooth axis): 0.1 mm (model 1a), 0.2 mm (model 1b), and 0.3 mm (model 1c), respectively. The element numbers given in Table II are almost the same for the 3 models.[9]

For the segmentation strategies 2, 3, and 4, to start with, mandibular bone and teeth were segmented (as separate tissues) from the CT data by using standard semiautomatic segmentation techniques as thresholds and region growing provided by the visualization

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