

## Periodontal Ligament Hydrostatic Pressure with Areas of Root Resorption after Application of a Continuous Torque Moment

*A Study Using Identical Extracted Maxillary Human Premolars*

Ansgar Hohmann<sup>a</sup>; Uwe Wolfram<sup>b</sup>; Martin Geiger<sup>a</sup>; Andrew Boryor<sup>a</sup>; Christian Sander<sup>a</sup>;  
Rolf Faltin<sup>c</sup>; Kurt Faltin<sup>d</sup>; Franz Guenter Sander<sup>e</sup>

### ABSTRACT

**Objective:** To evaluate the risk of root resorption, individual finite element models (FEMs) of extracted human maxillary first premolars were created, and the distribution of the hydrostatic pressure in the periodontal ligament (PDL) of these models was simulated.

**Materials and Methods:** A continuous lingual torque of 3 Nmm and 6 Nmm respectively was applied in vivo to the aforementioned teeth. After extraction, FEMs of these double-rooted teeth were created based on high-resolution microcomputed tomographics (micro CT, voxel size: 35 microns). This high volumetric resolution made the recognition of very small resorption lacunae possible. Scanning electron micrographs of the root surfaces were created as well. This enabled the investigation of advantages and disadvantages of the different imaging techniques from the viewpoint of the examination of root resorption. Using the FEMs, the same loading conditions as applied in vivo were simulated.

**Results:** The results of clinical examination and simulations were compared using the identical roots of the teeth. The regions that showed increased hydrostatic pressure ( $>0.0047$  MPa) correlated well with the locations of root resorption for each tooth. Increased torque resulted in increased high-pressure areas and increased magnitudes of hydrostatic pressure, correlating with the experiments.

**Conclusion:** If hydrostatic pressure exceeds typical human capillary blood pressure in the PDL, the risk of root resorption increases.

**KEY WORDS:** Root resorption; Hydrostatic pressure in the periodontal ligament; Finite element method; Human maxillary first premolars; Simulation; Continuous torque

### INTRODUCTION

Minimization of the risk of root resorption is important during orthodontic treatment. The biologic mech-

anisms of this process have not been fully studied but are known to be strongly dependent on individual factors of the patient. A multitude of factors influencing root resorption have been discussed. Genetic factors,<sup>1</sup> the mineral content of cementum,<sup>2</sup> and orthodontic forces and moments, as well as their duration during application, are believed to influence susceptibility to root resorption. Recent studies show that the extent of root resorption depends on the applied force system.<sup>3-6</sup> Schwarz<sup>7,8</sup> stated that root resorption can occur if capillary blood pressure is exceeded. In the literature, the range of capillary blood pressure is reported to be between 15 and 35 mm Hg (equivalent to 0.0020 to 0.0047 MPa).<sup>9,10</sup>

Casa et al<sup>4</sup> applied torque to human premolars in vivo, and after extracting them, they investigated the root resorption that occurred. They observed resorption lacunae on the linguoapical portion of the root and on the buccocervical third of the root.

<sup>a</sup>Research Scientist, Department of Orthodontics, University of Ulm, Ulm, Germany.

<sup>b</sup>Research Scientist, Institute of Orthopaedic Research and Biomechanics, University of Ulm, Ulm, Germany.

<sup>c</sup>Associate Professor, Department of Orthodontics, Paulista University, São Paulo, Brazil.

<sup>d</sup>Professor and Department Head, Department of Orthodontics, Paulista University, São Paulo, Brazil.

<sup>e</sup>Professor and Department Head, Department of Orthodontics, University of Ulm, Ulm, Germany.

Corresponding author: Mr Ansgar Hohmann, Universitätsklinikum Ulm, Department of Orthodontics, ZMK 4, Albert-Einstein-Allee 11, 89081 Ulm, Baden-Württemberg, Germany (e-mail: ansgar.hohmann@uni-ulm.de)

Accepted: August 2006. Submitted: June 2006.

© 2007 by The EH Angle Education and Research Foundation, Inc.

The goal of the present study was to simulate these experiments based on the same teeth. The distribution of the hydrostatic pressure in the periodontal ligament (PDL) of these double-rooted premolars was compared in a finite element model (FEM) with the results of the in vivo experiments of the same teeth for validation of the capillary blood pressure theory of Schwarz. It was assumed that a stress greater than blood pressure could make the capillary blood vessels in the PDL collapse.<sup>11</sup>

Stress in the PDL has been analyzed in the literature.<sup>9,10,12-14</sup> In single-rooted teeth stress maxima were found near the apex. To our knowledge, there are no existing studies using the identical teeth for simulation of orthodontic torque and comparing the results with root resorption on these teeth.

To date, root resorption and the mineralized structure of cementum have been examined only by scanning electron microscopy (SEM).<sup>3-5,15-17</sup> This is a rather difficult means of examining root resorption, as sputtering is necessary and the desired image view must be chosen before making an image. In this study, root resorption lacunae and their morphology were visualized by SEM and microcomputed tomography (micro CT) to show the advantages and disadvantages of these different visualization techniques.

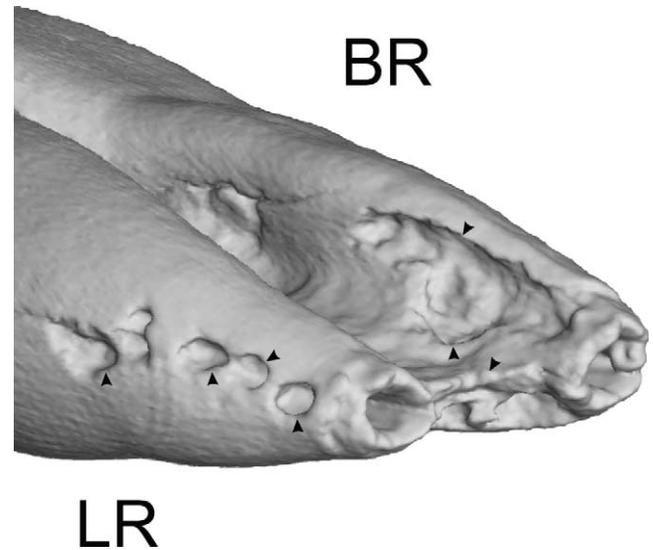
## MATERIALS AND METHODS

The extracted teeth used for this study came from an in vivo study performed by Casa et al.<sup>4</sup> They investigated root resorption in human maxillary first premolars after application of continuous torque moments (3 Nmm and 6 Nmm), using superelastic nickel-titanium–stainless steel springs for the application of the torque moments.

The continuity of the moments over a treatment time of 4 weeks was induced by temperature conditioning the wire at the Department of Orthodontics, Paulista University, São Paulo, Brazil.

After 4 weeks, the premolars were extracted. Clinically, the patients required the extraction of these teeth as part of their orthodontic treatment. All patients were informed about the procedures and their written consent was obtained. The study was authorized by the Medical Ethics Committee of the University of São Paulo.

The root surfaces were examined by SEM.<sup>4</sup> SEM is a rather difficult means of examining root resorption. Therefore, micro CT datasets (Institute of Orthopaedic Research and Biomechanics, Ulm, Germany) were created for the aforementioned teeth (3 Nmm torque and 6 Nmm torque) and compared with the SEM results. The resolution of the dataset was 35 microns. The density information in the micro CT dataset was



**Figure 1.** Isosurface view of the tooth treated by a torque of 6 Nmm. Resorption lacunae (arrows) are visible on the lingual sides of the lingual (LR) and buccal (BR) root parts.

**Table 1.** No. of Elements Used for the Different Models

Amount of Torque	No. of Elements	
	PDL	Tooth
3 Nmm	152,776	56,454
6 Nmm	165,254	61,541

used to create isosurface representations of the surface of the tooth roots. Figure 1 shows such an isosurface view of the tooth treated by a torque of 6 Nmm in the experiment.

Model generation and preprocessing for finite element analysis was performed by AMIRA (Mercury Computer Systems, Berlin, Germany), SURFACER (Ann Arbor, Mich) and ANSYS (Canonsburg, Penn), according to the method published by Clement et al.<sup>18</sup>

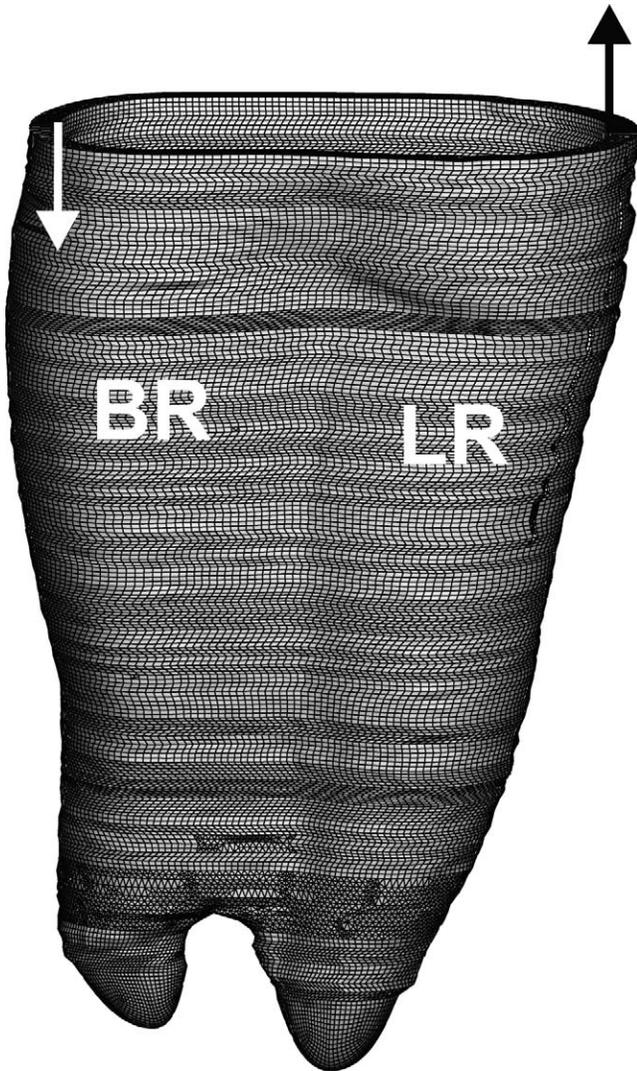
The PDL was constructed as a layer with a thickness of 0.3 mm around the tooth root. A sensitivity analysis with a single-rooted premolar showed that this was a justifiable approximation. The number of elements forming the tooth roots is shown in Table 1. This number differs between both tooth roots because individual meshes were created for the 3-Nmm tooth root and for the 6-Nmm tooth root.

Final preprocessing, finite element calculations, and postprocessing were performed in ABAQUS (Providence, RI). A linearly elastic constitutive equation was chosen for the PDL and the tooth (Table 2). Because resorption generally begins after a few weeks of force application, the time factor did not have to be considered. Thus, the goal is not to investigate the instantaneous reaction of the tooth to loading, but the stress distribution in the position of equilibrium. Figure 2 il-

**Table 2.** Parameters for the Mechanical Properties of Dentin, Enamel, PDL, and Alveolar Bone<sup>a</sup>

	Young's modulus (MPa)	Poisson's ratio
Dentin	18,600	0.3
PDL	0.1	0.45
Alveolar bone	1000	0.3
Enamel	79,000	0.3

<sup>a</sup> Modified from Dorow and Sander.<sup>9</sup>

**Figure 2.** Load situation and FEM simulating premolar torque of 6 Nmm.

illustrates the loading conditions of the numeric simulation of a torque also successfully performed by Dorow and Sander.<sup>9</sup>

Two forces working in opposite directions were applied to two nodes on the lingual and labial sides of the root near the alveolar crest. They resulted in a total lingual moment of  $M_y = 3 \text{ Nmm}$  or  $M_y = 6 \text{ Nmm}$ , re-

**Figure 3.** SEM of the root with torque of 6 Nmm applied. Resorption lacunae (arrows) are visible on the lingual sides of the lingual (LR) and buccal (BR) root parts.

spectively, and were used to simulate lingual torque. This approach was justified because only the relative position of the forces is important for simulation of a torque.

## RESULTS

Figure 3 shows an SEM image of the tooth under a torque of 6 Nmm. This high-resolution representation of the apical root part gives detailed information about the microscopic structure of the resorption lacunae. Very large resorption lacunae are visible in the lingual surfaces of the apical parts of the root.

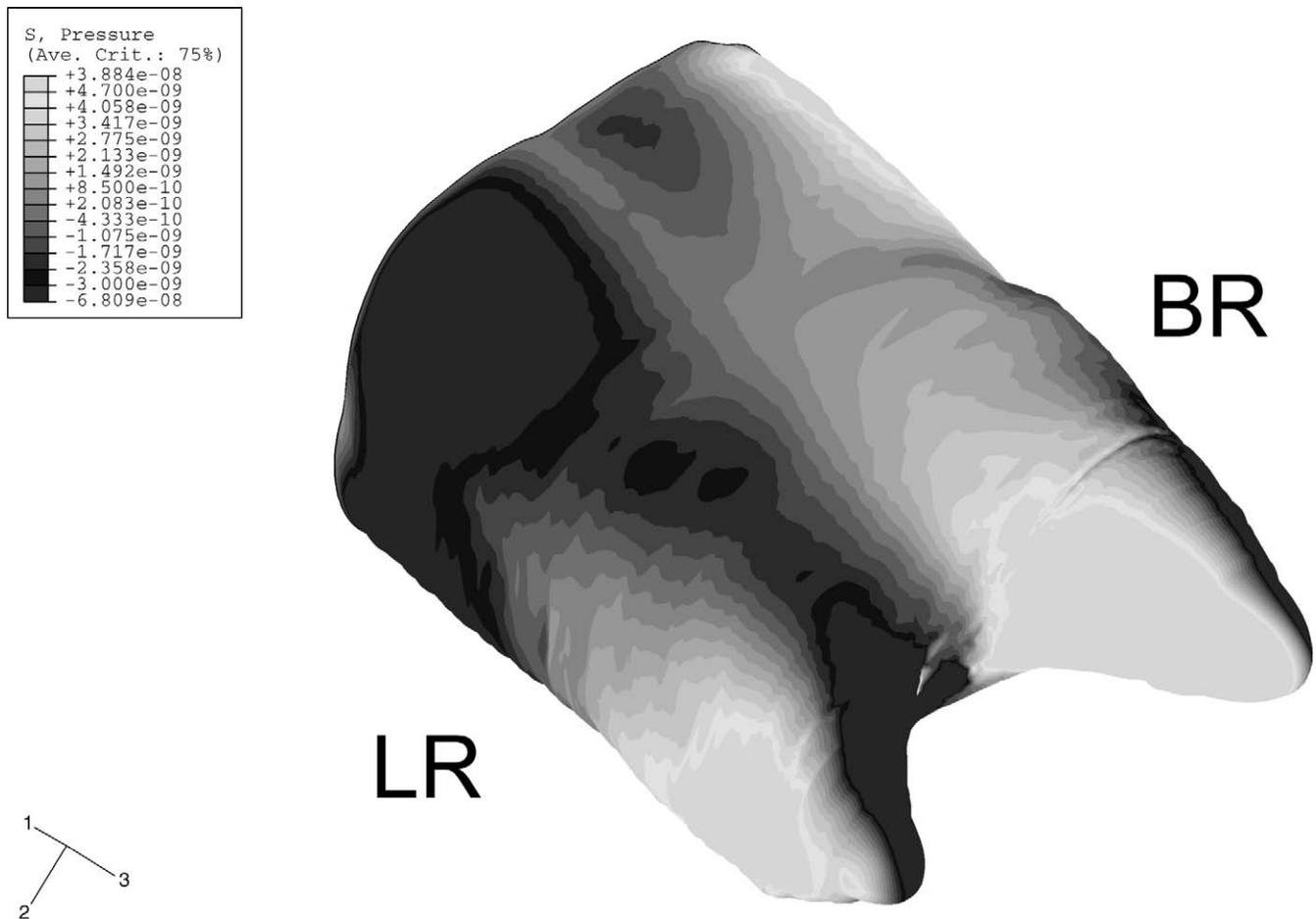
Figure 1 shows an isosurface view of the apical part of the same tooth based on micro CT. The morphology of the roots with resorption is clearly visible, but the resolution is too low for representation of the microscopic structure and the mineralized structure of cementum.

In this study, the hydrostatic pressure ( $p$ ), which is equal to  $\sigma_H = (\sigma_1 + \sigma_2 + \sigma_3)/3$  with hydrostatic stress  $\sigma_H$  and the principal stresses  $\sigma_1$ ,  $\sigma_2$  and  $\sigma_3$ , was calculated. In Figures 4 (3-Nmm tooth) and 5 (6-Nmm tooth), the pressure on the surface of the PDL is shown. This pressure also represents the pressure within the PDL. A test showed that pressure does not change significantly within the PDL in directions tangential to the surface of the PDL.

After 4 weeks of torque application (3 Nmm), Casa et al<sup>4</sup> observed resorption only at the lingual part of the two apical root parts. They also found some resorption lacunae at the buccocervical third of the root.

This corresponds to the pressure zones (greater than 0.0047 MPa, maximum literature value for capillary blood pressure<sup>9</sup>) resulting from the simulation of the same torque application to the same root (light grey areas in Figure 4).

The finite element calculations with the same root show regions of pressure exceeding 0.0047 MPa at



**Figure 4.** Profile of the hydrostatic pressure in the PDL of the tooth subjected to a torque of 3 Nmm (in TPa). The maxima of the hydrostatic pressure are on the lingual sides of the lingual and buccal root parts and in the buccocervical part of the root. Pressures above 0.0047 MPa are represented in light grey.

the buccocervical part of the root and overall lingual surfaces of the two apical root parts. There were no other resorption zones found in the experiments, and no other pressure zones exceeding 0.0047 MPa resulted from the simulations.

For a lingual torque of 6 Nmm, more and deeper resorption lacunae were observed linguoapically and buccocervically.

Figure 3 shows an SEM of the apical part of the root after 4 weeks of application of 6 Nmm of torque. Figure 5 shows the results of the finite element calculations with the same root and the same torque. Pressures above 0.0160 MPa are represented in grey. Pressures exceeding 0.0047 MPa can be observed on the lingual sides of the two apical root parts. Buccocervically, the simulations also showed an area with a pressure that exceeded 0.0047 MPa.

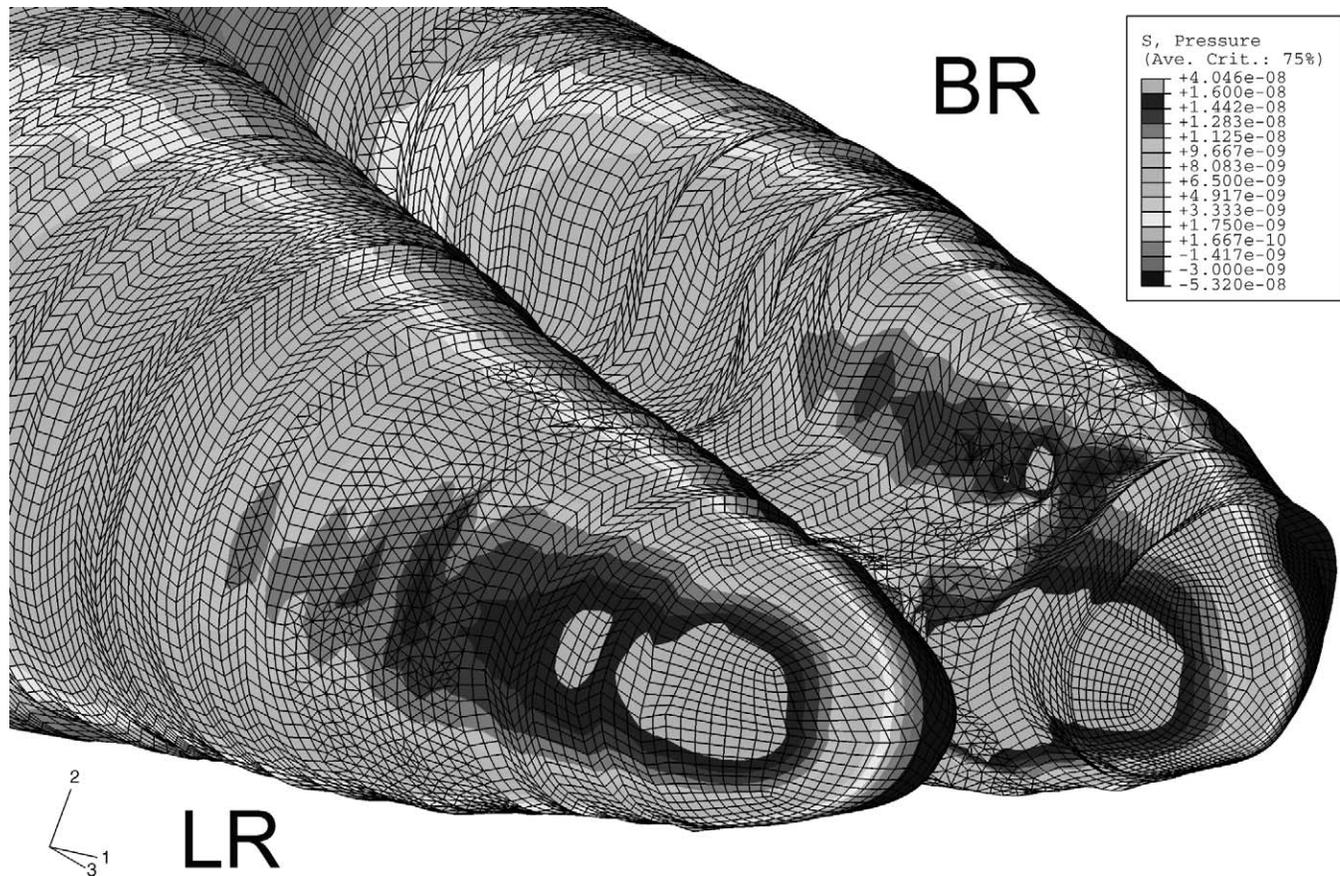
These high-pressure zones correspond to the zones where root resorption occurred in the experiment. The area of the buccocervical high-pressure zone is greater than the areas of the linguoapical high-pressure

zones. The pressure maximum in the buccocervical high-pressure zone is also greater than the pressure maxima of the linguoapical high-pressure zones.

## DISCUSSION

SEM is a rather difficult method of examining tooth roots for resorption because the desired image view must be chosen before an image is created. By contrast, during micro CT imaging, a dataset of the whole tooth is recorded and sputtering is not necessary. During computer-aided image processing, the investigator can choose any image view desired. Furthermore, it is possible to investigate the resorption lacunae volumetrically, as described by Geiger et al.<sup>19</sup>

Although SEM gives much more detailed information about the resorption lacunae and the mineralized structure (Figure 3), the micro CT dataset gives the morphology of the root with resorption lacunae, which makes identification of the major resorption lacunae easier (Figure 1). If only morphologic information



**Figure 5.** Profile of the hydrostatic pressure in PDL of the tooth subjected to a torque of 6 Nmm (in TPa). Pressures above 0.0160 MPa are represented in grey.

about the resorption lacunae is required, micro CT can be an interesting alternative.

In regions where the capillary blood pressure was not exceeded, no root resorption occurred. This indicated that there seems to be no risk of root resorption in regions where the capillary blood pressure is not exceeded. In regions of the tooth root where the capillary blood pressure exceeded 0.0047 MPa (bucco-cervically and linguoapically), root resorption was observed in this study.

After application of a torque of 6 Nmm, the root resorption was greater than for the teeth that received 3 Nmm of torque in the *in vivo* experiments. This agrees with the simulations, in which more extended high-pressure zones were observed for the 6-Nmm teeth than for the 3-Nmm teeth. The hydrostatic pressure in the PDL obviously depends on the magnitude of the force being applied. This contradicts the findings of Owman-Moll et al<sup>20,21</sup> and Maltha et al<sup>22</sup> but is in agreement with the findings of Faltin et al,<sup>3,6</sup> Casa et al,<sup>4</sup> and Chan and Darendeliler,<sup>5</sup> who observed that the extent of root resorption depended on the magnitude of the applied force system.

Simulations performed by Dorow and Sander<sup>9</sup> of a

single-rooted mandibular first premolar with a lingual torque show that increased hydrostatic pressure can be observed at the linguoapical and the buccocervical parts of the PDL. This observation was confirmed in this study of double-rooted teeth. There were no other high-pressure zones apart from those shown in the simulations.

For lingual torque, the highest pressures and the largest high-pressure areas were observed at the buccal part of the PDL near the alveolar crest. One would expect root resorption that is at least as severe as in the apical part, but this was not observed *in vivo*. This indicates that a difference in dentoclast activity may reduce the sensitivity of the root to resorption in the cervical third.

The different blood sources for vascularization of the PDL may also play a part, depending on the position in the PDL considered. The cervical third is also connected with the suprapariosteal arteries, while the apical third of the PDL is near the arteria dentalis.<sup>23</sup> The distribution of capillary blood pressure along the PDL is not known but might also contribute to the differences.

Apical cementum is softer than cervical cementum

and there are fewer Sharpey's fibers, which may play a part in resorption susceptibility.<sup>24,25</sup> Henry and Weinmann<sup>26</sup> discovered that the apical third of the root is more susceptible to root resorption than the cervical third. Because the cervical acellular cementum is more mineralized than the apical cellular cementum, it is possible that the mineral content influences susceptibility to resorption.

An increase in hydrostatic pressure and increases in high-pressure areas (higher than 0.0047 MPa) corresponded with more severe root resorption. Preceding calculations simulating intrusion showed the same results.

Further studies are necessary to determine whether the increased magnitude of hydrostatic pressure or the increased area of the high-pressure zones is responsible for the more severe root resorption during increased torque. The dysfunction of blood supply in larger PDL regions may be a cause of more severe root resorption. An improvement of the calculation method is required for a better understanding of root resorption.

In furcations of the roots, the simulations as well as the in vivo experiments showed no sign of local pressure maxima or resorption lacunae, respectively. This is in contradiction to the intrusion of teeth, during which an increased risk for root resorption near the furcation of the roots<sup>3</sup> is present.

Areas with stress in the simulations (buccoapically and linguocervically) did not show root resorption in vivo. This is in disagreement with Han et al,<sup>16</sup> who observed root resorption during the extrusion of teeth. An explanation could be the different application systems and application periods used in each study.

The individual resorption lacunae and their typical hemispheric shape<sup>17</sup> could not be found by these simulations, but pure geometric causes can be excluded as an explanation. Perhaps micromechanical properties resulting from distribution of Sharpey's fibers in root cementum play a part. Maxima of hydrostatic pressure were observed in the apical thirds of the roots, in agreement with the findings of Dorow and Sander<sup>9</sup> and Rudolph et al<sup>27</sup> (studies with single-rooted teeth).

## CONCLUSIONS

- a. It is possible to examine root resorption by micro CT imaging if only morphologic information is required.
- b. If the hydrostatic pressure rises above 0.0047 MPa, a decisive condition for root resorption is fulfilled, but other factors such as the location of the pressure on the root may also influence the severity of resorption.

- c. Hydrostatic pressure is one of the indicators of the regions in which root resorption can occur.
- d. Individual factors have an additional effect on root resorption.

## ACKNOWLEDGMENTS

The authors thank the Deutsche Forschungsgemeinschaft for financial support of project 272/6-1 and 272/7-1.

## REFERENCES

1. Al-Qawasmi RA, Hartsfield JK, Everett ET, Weaver MR, Foroud TM, Faust DM, Roberts WE. Root resorption associated with orthodontic force in inbred mice: genetic contributions. *Eur J Orthod*. 2006;28:13–19.
2. Rex T, Kharbanda OP, Petocz P, Darendeliler MA. Physical properties of root cementum: part 6. A comparative quantitative analysis of the mineral composition of human pre-molar cementum after the application of orthodontic forces. *Am J Orthod Dentofacial Orthop*. 2006;129:358–367.
3. Faltin RM, Arana-Chavez VE, Faltin K, Sander FG, Wichelhaus A. Root resorption in upper first premolars after application of continuous intrusive forces. Intra-individual study. *J Orofac Orthop/Fortschr Kieferorthop*. 1998;59:208–219.
4. Casa MA, Faltin RM, Faltin K, Sander FG, Arana-Chavez VE. Root resorption in upper first premolars after application of continuous torque moment. Intra-individual study. *J Orofac Orthop/Fortschr Kieferorthop*. 2001;62:285–295.
5. Chan E, Darendeliler MA. Physical properties of root cementum: part 5. Volumetric analysis of root resorption craters after application of light and heavy orthodontic forces. *Am J Orthod Dentofacial Orthop*. 2005;127:186–195.
6. Faltin RM, Faltin K, Sander FG, Arana-Chavez VE. Ultrastructure of cementum and periodontal ligament after continuous intrusion in humans: a transmission electron microscopy study. *Eur J Orthod*. 2001;23:35–49.
7. Schwarz AM. Das biologische Verhalten orthodontisch beanspruchter Zähne. *Zeitschr Zahnärztl Orthop*. 1929;4:113–117.
8. Schwarz AM. Die Gewebsveränderung bei orthodontischen Maßnahmen. *Fortschrit Orthodontik Theorie Praxis*. 1931;1:381–407.
9. Dorow C, Sander FG. Development of a model for the simulation of orthodontic load on lower first premolars using the finite element method. *J Orofac Orthop/Fortschr Kieferorthop*. 2005;66:208–218.
10. Dorow C. *Numerische Simulation und experimentelle Untersuchung der Zahnbewegung*. [Dissertation]. Ulm: Universität Ulm; 2004.
11. Choy K, Pae EW, Park Y, Kim KH, Burstone CJ. Effect of root and bone morphology on the stress distribution in the periodontal ligament. *Am J Orthod Dentofacial Orthop*. 2000;117:98–105.
12. Jeon PD, Turley PK, Moon HB, Ting K. Analysis of stress in the periodontium of the maxillary first molar with a three-dimensional finite element model. *Am J Orthod Dentofacial Orthop*. 1999;115:267–274.
13. McGuinness N, Wilson AN, Jones M, Middleton J, Robertson NR. Stresses induced by edgewise appliances in the periodontal ligament—a finite element study. *Angle Orthod*. 1992;62:15–22.
14. Wilson AN, Middleton J, Jones ML, McGuinness NJ. The finite element analysis of stress in the periodontal ligament

- when subject to vertical orthodontic forces. *Br J Orthod.* 1994;21:161–167.
15. Acar A, Canyürek Ü, Kocaaga M, Erverdi N. Continuous vs. discontinuous force application and root resorption. *Angle Orthod.* 1999;69:159–164.
  16. Han G, Huang S, Von den Hoff JW, Zeng X, Kuijpers-Jagtman AM. Root resorption after orthodontic intrusion and extrusion: an intraindividual study. *Angle Orthod.* 2005;75:912–918.
  17. Chan EKM, Petocz P, Darendeliler MA. Validation of two-dimensional measurements of root resorption craters on human premolars after 28 days of force application. *Eur J Orthod.* 2005;27:390–395.
  18. Clement R, Schneider J, Brambs HJ, Wunderlich A, Geiger M, Sander FG. Quasi-automatic 3D finite element model generation for individual single-rooted teeth and periodontal ligament. *Comput Methods Programs Biomed.* 2004;73:135–144.
  19. Geiger M, Hohmann A, Boryor A, Faltin RM, Faltin K, Sander FG. Volumes of root resorption lacunae in upper first premolars after application of continuous orthodontic forces. In: Davidovitch Z, Mah J, eds. *Biological Mechanisms of Tooth Movement and Craniofacial Adaptation*. Boston, MA: Harvard Society for the Advancement of Orthodontics; In press.
  20. Owman-Moll P, Kuroi J, Lundgren D. Effects of a doubled orthodontic force magnitude on tooth movement and root resorption. An inter-individual study in adolescents. *Eur J Orthod.* 1996;18:141–150.
  21. Owman-Moll P, Kuroi J, Lundgren D. The effects of a four-fold increased orthodontic force magnitude on tooth movement and root resorption. An intra-individual study in adolescents. *Eur J Orthod.* 1996;18:287–294.
  22. Maltha JC, van Leeuwen EJ, Dijkman GEHM, Kuijpers-Jagtman AM. Incidence and severity of root resorption in orthodontically moved premolars in dogs. *Orthod Craniofacial Res.* 2004;7:115–121.
  23. Schroeder HE. *Orale Strukturbiologie*. 4th ed. Stuttgart: Thieme; 1992.
  24. Malek S, Darendeliler MA, Swain MV. Physical properties of root cementum: part I. A new method for 3-dimensional evaluation. *Am J Orthod Dentofacial Orthop.* 2001;120:198–208.
  25. Srivicharnkul P, Kharbanda OP, Swain MV, Petocz P, Darendeliler MA. Physical properties of root cementum: part 3. Hardness and elastic modulus after application of light and heavy forces. *Am J Orthod Dentofacial Orthop.* 2005;127:168–176.
  26. Henry JL, Weinmann JP. The pattern of resorption and repair of human cementum. *J Am Dent Assoc.* 1951;42:270–290.
  27. Rudolph DJ, Willes MG, Sameshima GT. A finite element model of apical force distribution from orthodontic tooth movement. *Angle Orthod.* 2001;71:127–131.