

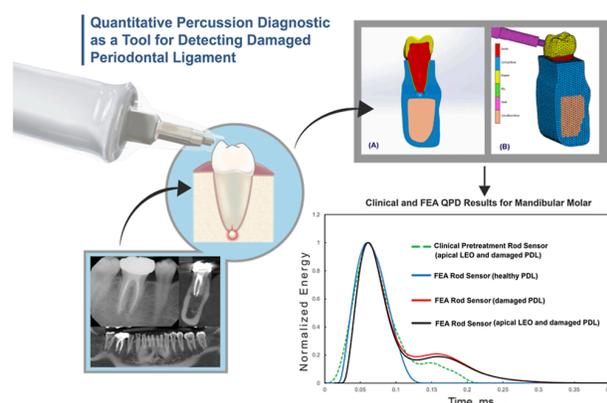
RESEARCH ARTICLE

Exploratory investigation of quantitative percussion diagnostics in endodontic health and pathology

Seeing the unseen

Jie Shen, PhD^{a,b}; Clifford J. Ruddle, DDS^c; John West, DDS, MSD^d;
Cherilyn G. Sheets, DDS^e; James C. Earthman, PhD^{a,f}

^aDepartment of Materials Science and Engineering, University of California, Irvine, Irvine, CA; ^bNow with Perimetrics, Inc, Redmond, WA; ^cDepartment of Endodontics, University of Pacific, Arthur A. Dugoni School of Dentistry, San Francisco, CA; ^dDepartment of Endodontics, University of Washington, Seattle, WA; ^eResearch and Teaching Divisions, Newport Coast Oral Facial Institute, Newport Beach, CA; ^fDepartment of Biomedical and Engineering, University of California, Irvine, Irvine, CA.



Why Is This Important?

This study validates quantitative percussion diagnostics for detecting microgap defects at early stages in the periodontium. Combining clinical data and finite element analysis simulations, results show that quantitative percussion diagnostics objectively identify periodontal ligament damage before radiographic evidence.

© 2025 The Author(s). Published by Elsevier Inc. on behalf of the American Dental Association. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

<https://doi.org/10.1016/j.jfscie.2025.100060>

Abstract

Background. Quantitative percussion diagnostics (QPD) have been able to detect coronal microgap defects (MGDs) at early stages. Specifically, QPD identified early MGDs associated with restorative luting failures, coronal and radicular root fractures, and implants. Another potential MGD for teeth is a defective periodontal ligament (PDL). If there is early attachment apparatus disease, there is a high probability that the PDL is damaged. This study investigated the QPD response of a tooth with a lesion of endodontic origin (LEO) to determine if the damaged PDL can be detected.

Methods. An in vivo tooth with a periapical LEO was clinically evaluated by using radiographs, cone-beam computed tomographic images, and QPD. Finite element analysis (FEA) was used to accurately model this same tooth to simulate the apical LEO in the model. Reduced moduli in tissue components were used to simulate the effect of the LEO. The clinical QPD result was validated using FEA for an endodontically failing mandibular first molar with an apical LEO.

Results. The in vitro FEA results show consistent features with the corresponding clinical QPD results and validate that the model closely replicates the tooth and the LEO observed with radiographic and cone-beam computed tomographic images. It was also shown that these FEA results and clinical QPD results yield nearly the same normal fit error values.

(Continued on next page)

Conclusions. The agreement between this in vitro FEA model and the in vivo clinical QPD results for a mandibular molar with an apical LEO indicates that QPD can detect a damaged PDL.

Key Words. Quantitative percussion diagnostics; lesion of endodontic origin; cone-beam computed tomography; finite element analysis; dental biomechanics; normal fit error; energy return graph.

Introduction

A frequently encountered clinical dilemma for dentists is the identification of early endodontic disease emanating from pulpal breakdown. The etiology of pain is often challenging because a patient can become symptomatic before radiographic confirmation of a lesion of endodontic origin (LEO). In fact, many asymptomatic or symptomatic patients with early irreversible pulpal breakdown do not show a LEO on radiographic examination.

It has been established by Stashenko et al¹ that infection of the dental pulp stimulates a host immune response in the attachment apparatus with concomitant resorption of the PDL and bone. It is recognized that any radiographic LEO arises initially within the PDL, secondary to pulpal breakdown and the egress of irritants along the anatomic pathways of the root canal system.^{2,3} A LEO can remain free of symptoms and therefore be unidentified unless a radiographic examination is performed.^{3,4} The tests for detecting a LEO include conducting a clinical examination, including periodontal probing; performing pulpal sensibility tests; and obtaining 2-dimensional or 3-dimensional (3D) imaging as well as other traditional techniques.^{2,3,5} However, most of these techniques often rely on visual or subjective determinations of the tooth in a nonloaded state. In contrast, the breakdown of the periodontal ligament (PDL) can occur relatively early. Because a damaged PDL is only a few tenths of a millimeter in width, its loss may mechanically behave in a manner similar to other microgap defects (MGDs) observed in teeth, such as coronal and radicular cracks or loose restorations.⁶⁻¹³

A mechanical testing methodology called quantitative percussion diagnostics (QPD) has shown an ability to detect MGDs (cracks) and other structural abnormalities in teeth and implants as well as the mechanical integrity of the supporting bone around implants.⁶⁻¹³ QPD is an electromagnetically driven percussion system that works by lightly tapping on the buccal or facial surface of a tooth, allowing the handpiece sensor to collect the resultant force as a function of time. More details on the operation of QPD for testing of teeth and implants have been published elsewhere.⁶⁻¹⁴

QPD has identified cracks and defects in teeth with a 98% agreement with blinded tooth disassembly performed under the operating microscope.⁸⁻¹² When QPD is used on intact teeth that are endodontically and periodontally healthy, an energy return graph (ERG) plots a single bell-shaped peak.^{13,14} However, the ERG has a different shape when there is internal mobility that results from an MGD. In these instances, the ERG exhibits the presence of an additional peak or peaks. A normal fit error (NFE) parameter has been used to numerically quantify the deviation in response shape from a normal single peak compared with an unhealthy multiphase ERG plot. This NFE parameter quantifies the severity of

defect damage as measured by the increasing level of internal mobility (oscillations) within the structure.⁹⁻¹³

These diagnostic detection needs are increasing in the human population because people are living longer and therefore using their teeth longer. Teeth wear out and produce symptoms that require proper diagnosis and treatment. The average US life expectancy is now longer than 77 years, which means we chew on our permanent teeth for more than 7 decades. It is estimated that teeth experience about 1 million significant loading repetitions per year.¹ That's 70 million significant loading repetitions for the human permanent dentition. The longer people live, the longer they need improved diagnostics. QPD has the capacity for dentists to see mechanically what they cannot see visually to help prevent unmonitored dental breakdown.¹⁵ QPD can easily be incorporated into the routine chairside care by having a 2 through 3 second QPD test for each tooth, or 2 through 3 minutes for the entire mouth. The data collected on the overall and internal mobility of each site will give new, valuable data for the clinician to assess.

Finite element analysis (FEA) is often used by biomedical researchers as a modeling tool to better understand clinical findings. A better understanding of QPD results was achieved through the development of FEA models of both intact and cracked teeth. Previous studies show that a multiphase QPD response for a cracked tooth is caused by crack surface oscillations.^{13,14} Our study aimed to see if these FEA models can simulate the QPD data obtained in vivo for an endodontically failing tooth with a confirmed apical LEO. The hypothesis was that an in vivo QPD test and resultant ERG plot data for a tooth with an apically positioned LEO can be better understood by modeling it using FEA.

Methods

Radiographs and clinical examinations

A 25-year-old woman was enrolled in an institutional review board-approved study at Sheets, Paquette & Wu Dental Practice, and informed consent was obtained. On radiographic examination, the mandibular right first molar (tooth no. 30) was endodontically failing and had an apical LEO associated with the distal root (Figure 1A). Radiographic monitoring revealed the LEO was increasing in size after the original treatment. Cone-beam computed tomography (CBCT) further confirmed an apical distal root radiolucency and provided a 3D perspective (Figure 1B). An image of CBCT depicting a coronal view of the same tooth provided more shape detail of the apical LEO (Figure 1C). QPD testing was performed using InnerView (Perimetrics, Inc) before endodontic retreatment and at a 24-month follow-up visit.

The patient's history showed that endodontic treatment was performed more than 2 years before, and without the



Figure 1 A. A radiographic image of a mandibular first right molar depicting an apical lesion of endodontic origin (LEO) associated with the distal root. B. A cone-beam computed tomographic image of the mandible reveals a LEO associated with the distal root of the mandibular first right molar. C. A cone-beam computed tomographic image (proximal view) depicting the apical LEO.

subsequent placement of a protective restoration. A radiographic image revealed incomplete endodontic treatment, a missed canal, and underfilled canals, and attachment apparatus disease (Figure 1). After examination, the endodontist recommended retreatment to reverse the disease process, followed by a protective restoration to stabilize the tooth, then periodic recall examinations to evaluate healing, or the lack thereof.^{4,5}

FEA modeling

The apical LEO shown in Figure 1 was replicated into a computer-aided design (CAD) model of a molar used for FEA simulations. The QPD in vitro results were compared with the in vivo results to provide further validation of the FEA modeling and to increase understanding of the mechanical responses of PDL damage associated with a LEO.

These finite element models simulate the anatomy of an individual tooth complex, including enamel, cementum, dentin, pulp chamber, related canals, PDL, and bone. A human mandibular molar CAD model was developed using SolidWorks (Dassault Systèmes SolidWorks Corp) and 3D human digital tooth anatomy data, courtesy of eHuman, Inc.

The bone was modeled using the CBCT scan of this tooth (Figure 1) to closely replicate the in vivo LEO with a space at the distal root apex (Figure 2). A rigid boundary condition was imposed only at the mesial and distal sides of this bone model. The percussion rod is also included in the CAD assembly to simulate QPD. The CAD models of the tooth assembly and percussion rod were meshed in MSC Apex (Hexagon). These FEA meshes have a total number of about 0.55 million elements. Second-order isoparametric 3D-node tetrahedron elements were meshed for the PDL. Eight-node isoparametric arbitrary hexahedral elements were meshed for the percussion probe. Linear isoparametric 3D tetrahedron elements were meshed for the remaining tooth components. The initial condition was defined by tapping the percussion rod on the tooth, which simulates the clinical test of the QPD. Boundary conditions were defined to constrain the elements on the outer surfaces of the supporting bone.

Material properties reflecting weakened tooth structure and damaged PDL and bone were implemented in the FEA components, which aligned with the presenting clinical pathology. Specifically, reduced elastic moduli of healthy enamel and dentin were used, as endodontic treatment weakens a tooth's microstructure, decreasing stiffness by up to 63%.^{16,17} Specifically, a reduced Young modulus in the enamel portion of

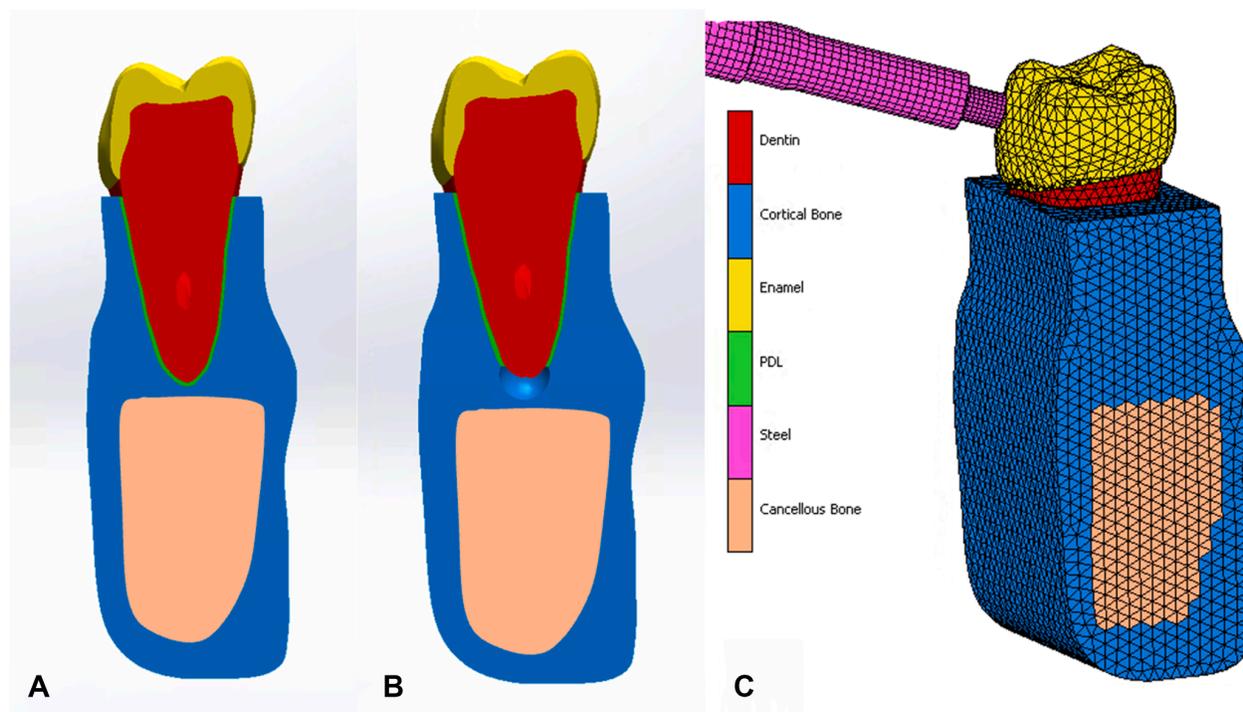


Figure 2 **A.** A coronal cross-section of the model used for finite element analysis models of a healthy periodontal ligament (PDL) and a damaged PDL without a lesion of endodontic origin. **B.** A coronal cross-section of the model of a damaged PDL with an apical lesion of endodontic origin. **C.** A 3-dimensional mesh of this model with the different materials indicated.

the tooth of 8.41 GPa and a reduced Young modulus in the dentin portion of the tooth of 5.88 GPa were used. The modulus of the PDL was also reduced from 0.1 MPa for a healthy PDL to determine whether the FEA response could reasonably match the QPD response measured in vivo. The material properties of the dental system include the elastic Young modulus, Poisson ratio, and mass density. The values used for these properties were derived from those reported in earlier works and are listed in Table 1.^{14,18-21}

Results

A comparison between a normalized ERG plot as a function of time for the FEA model (black solid curve) and the endodontically failing tooth clinical result before treatment (green dashed curve) is shown in Figure 3. It can be seen in Figure 3 that a reasonable approximation of the clinical results was achieved by only reducing the PDL modulus from 0.1 MPa to 0.0045 MPa. For comparison, results for an FEA model that only contained a damaged PDL without the LEO are also shown (red solid curve). There is little difference between this result and that for the damaged PDL and LEO together. Thus, the difference in the QPD results between an intact tooth with a healthy PDL and that for a PDL with a LEO is primarily because of the damage in the PDL as opposed to the LEO itself. A reasonably accurate

match between the FEA results and the clinical data is also evident by comparing their NFE values. In particular, the NFE value predicted by the FEA simulation (apical LEO and damaged PDL) was 0.027, and the NFE value for the clinical QPD result was 0.029.

A simple cortical bone block model was used in previous FEA simulations of QPD responses for both intact¹³ and cracked molars.¹⁴ However, scans of this molar using CBCT made it possible to model the geometry of the bone and lesion more closely. A comparison of results for the simple cortical bone block and a more accurate bone geometry for an intact tooth with a healthy PDL (PDL modulus = 0.1 MPa) is given in Figure 4, which shows that using the more accurate bone geometry did not strongly alter the FEA results for a healthy intact tooth PDL. However, we opted to use the more accurate bone geometry model for the following results to make sure that using simple block bone geometry in the presence of an LEO did not lead to a substantial difference in results.

Relative acceleration between the inner and outer surface of a healthy PDL (black dotted curve) compared with that for a molar with the apical LEO and damaged PDL (black solid curve) were also plotted as a function of time in Figure 4. The relative acceleration characterizes how a PDL may be oscillating during percussion loading that could produce measurable force oscillations.¹³ It is

Table 1 Properties of dental tissues.^{14,18-21}

Material	Young Modulus, MPa	Poisson Ratio	Density, kg/m ³	Mass Matrix Multiplier	Stiffness Matrix Multiplier
Enamel	84,100; 8140*	0.33	2970	0	0
Dentin	14,700; 5880*	0.31	2410	0.0907	3×10^{-5}
Crack tip damage zone (dentin)	1470	0.31	2410	0.0907	3×10^{-5}
Periodontal ligament	0.1; 0.006†	0.45	1200	1,814	0.6
Cortical bone	14,700	0.3	1300	0.0907	3×10^{-5}
Cancellous bone	1370	0.3	1300	0.0907	3×10^{-5}

* Estimated values corresponding to enamel and dentin in the previously endodontically treated tooth (Figure 1). † Estimated value for an apical lesion of endodontic origin shown in Figure 1.

calculated by subtracting the acceleration of the inner surface of the PDL from the acceleration of the outer surface of the PDL. We noted that the effective mass of the tooth multiplied by this differential acceleration produces the force oscillation detected by the sensor in the percussion rod (ie, force = mass × acceleration).¹³ It can be seen in Figure 4 that the damaged PDL (black solid curve) oscillates with a much higher amplitude than a healthy PDL does (black dotted curve). We also noted that the oscillation in relative acceleration occurs about 0.02 milliseconds before the corresponding force oscillation is measured by the sensor in the rod. This time difference is expected as it corresponds to the time needed for the propagation of a stress wave from the PDL to the rod sensor at the speed of sound.¹³

The QPD result for a 24-month follow-up visit still exhibits a second peak (blue dashed curve in Figure 3), although somewhat delayed compared with the second peak at pretreatment. This delay suggests that the damping capacity of the PDL may have increased with healing, as would be expected. Figure 5 shows the same radiographic documentation as in Figure 1, but at 24 months posttreatment. Even though the recall radiograph indicates bone regeneration, the results in Figure 3 indicate that the periradicular tissues (bone and PDL) were still normalizing after the follow-up visit (blue dashed line). This finding is consistent with the FEA prediction that the presence of the LEO itself does not strongly affect QPD results.

Table 2 summarizes the NFE values predicted by FEA simulations and clinical QPD results. The NFE value for the

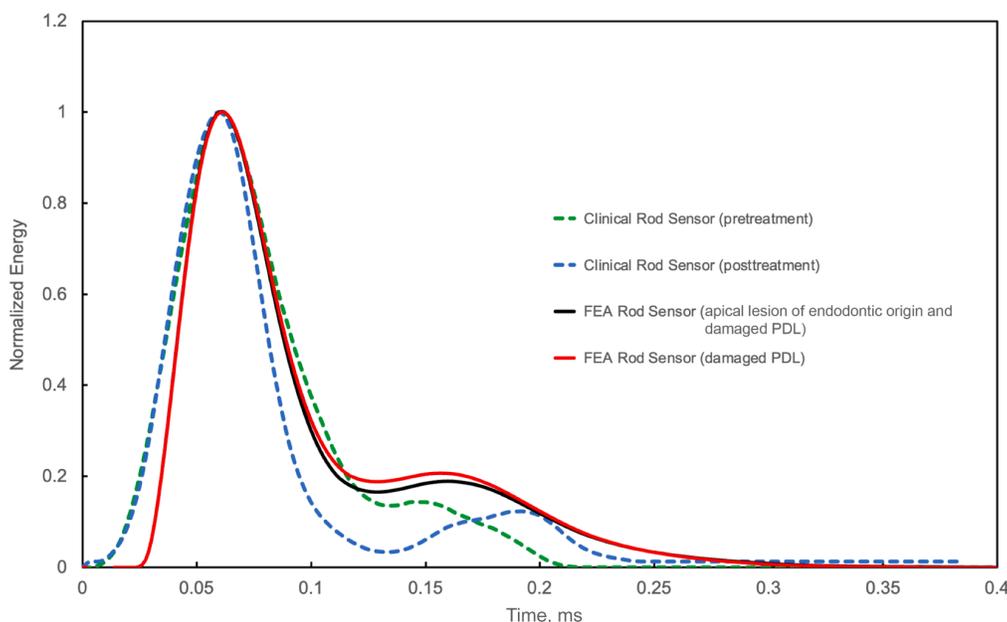


Figure 3 Clinical and finite element analysis (FEA) quantitative percussion diagnostics results for a mandibular molar. Clinical rod sensor data are indicated by a green dashed line (in vivo). FEA rod sensor simulations are indicated by black (apical lesion of endodontic origin and damaged periodontal ligament [PDL]) and red (damaged PDL) curves. Only the modulus of the PDL was reduced to 0.0045 MPa to simulate a damaged PDL in these models.

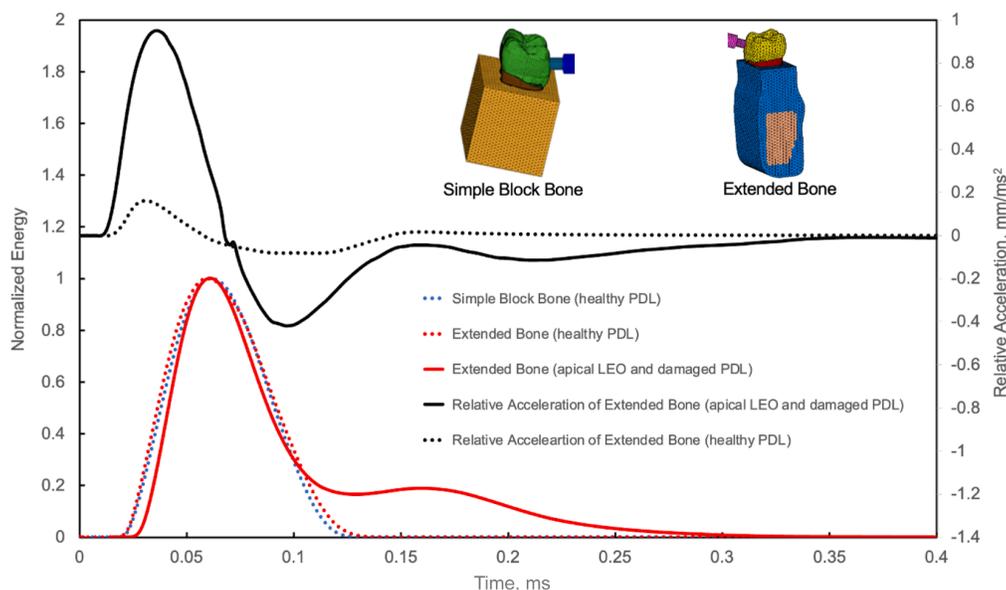


Figure 4 Finite element analysis quantitative percussion diagnostics result (red dotted curve) for an intact molar with a healthy periodontal ligament (PDL) (Figure 2A) and one (red solid curve) with a damaged PDL and lesion of endodontic origin (LEO) (Figure 2B). For comparison, corresponding healthy PDL results in which a simple block was used (blue dotted curve) bone is also shown. In addition, relative acceleration of the periradicular sides of the PDL is indicated by the black solid and dotted curves that correspond to a damaged PDL with LEO and a healthy PDL with no LEO, respectively.

FEA model of an undamaged intact molar was 0.014. The NFE value for the FEA model of a damaged PDL and LEO was 0.027, which was in good agreement with the clinical NFE value of 0.029.

Discussion

Comparison of the *in vitro* FEA results to the clinical *in vivo* QPD results shows that the features closely match. For example, the FEA ERG curves exhibit the same shape as the clinical ERG curves with double peaks, mirroring the first peak, valley, and width in time, shown in Figure 4. The relative amplitude of the second peak predicted by the FEA model correlates well with that for the clinical data. Although the total time duration is slightly longer for the FEA result compared with clinical data, the overall match between the FEA and clinical data is evident in terms of curve shape, number of peaks, peak amplitudes, and peak widths.

The clinical and FEA QPD results for a tooth with a LEO exhibit a decreased second amplitude peak. Numerous PDL moduli were explored in our FEA simulations to match FEA results to clinical QPD results better. Although no exact match was achieved, a close match was accomplished by reducing the PDL modulus to approximately 0.0045 MPa from its healthy value of 0.1 MPa. This reduction is reasonable considering how damaging a periradicular LEO is to surrounding tissue. Overall, this

agreement indicates that QPD's capability to detect periradicular endodontic pathology stems from the damaging effect of a LEO on the adjacent PDL tissue.

There was a one-to-one correlation between peaks in the relative acceleration of the PDL surfaces and the peaks in the ERG (Figure 4). This correlation indicates that the peaks measured from the percussion rod are caused by the oscillation of the PDL during percussion loading. This type of correlation between oscillations taking place in an intact tooth was also observed for a cracked molar in a previous study.¹³ The blue dashed line in Figure 4 shows a plot progression of ERG results that could be trending toward a normal response.

In the future, researchers could expand on our study by matching additional ERG data from a wider range of *in vivo* patients to strengthen the statistical robustness of the findings. Identifying and analyzing teeth with documented histories of endodontic treatment of lesions would provide clinical correlations. Simulating these patients and comparing them with their QPD results would help validate the diagnostic potential of the QPD method and further the understanding of its ability to detect early damage in the PDL. Future studies will also explore the early stages of PDL damage associated with other defects, such as incomplete vs complete vertical root cracks, to validate if QPD can identify a root crack before osseous breakdown, and, more specifically, the actual architecture of the root crack, as to whether the crack involves the epithelial attachment.



Figure 5 **A.** A recall radiograph of the mandibular right first molar shows that the original distal root apical lesion of endodontic origin has healed. **B.** A recall cone-beam computed tomographic image of the mandibular arch provides further evidence that the distal root apical lesion of endodontic origin has healed. **C.** A recall cone-beam computed tomographic image (coronal view) shows excellent endodontic healing.

Table 2 Normal fit error values for mandibular molar.

Tooth Condition	Normal Fit Error Value
FEA* rod sensor (undamaged)	0.014
Clinical rod sensor (pretreatment)	0.029
Clinical rod sensor (posttreatment)	0.022
FEA rod sensor (apical lesion of endodontic origin and damaged periodontal ligament)	0.028
FEA rod sensor (damaged periodontal ligament)	0.027

*FEA: Finite element analysis.

For this damaged PDL, the normalized energy return as a function of time tends to exhibit a distinctive pattern comprised a high amplitude peak followed by a smaller second peak. The modulus of the PDL plays a crucial role when simulating this endodontic treatment that resulted in a damaged PDL. The relative acceleration of the periradicular sides of the PDL was compared with the normalized energy return plot, which indicated that peaks were associated with oscillation of the damaged PDL under percussion loading. These results are consistent with the relative acceleration of crack faces in teeth reported earlier.¹³

Conclusions

The FEA in vitro results align well with clinical QPD data for a tooth with an apical LEO. These findings are consistent with peak amplitude, number of peaks, peak valley depth, time duration, and peak width. Thus, QPD proves effective in detecting the internal mobility associated with MGDs, including a damaged PDL resulting from a LEO.

Disclosure

Drs Earthman and Sheets are the inventors of quantitative percussion diagnostics. They founded Perimetrics, Inc, after some of their research efforts with this technology, and currently maintain a minority stock ownership in the company. Numerous patents have been issued and are pending (US-12372446-B2, US-12369846-B2, US-12257119-B2, US-12082940-B1, US-11906484-B2,

US-11604115-B2, US-11493415-B2, US-11488062-B1, US-10488312-B2, US-D850618-S, US-D821580-S, US-9869606-B2, US-9358089-B2, US-20130174639-A1, US-20110311944-A1). Dr Shen is employed by Perimetrics, Inc. None of the other authors reported any disclosures.

Email shenj8@uci.edu. Address correspondence to Dr Shen.

This study was funded through a research agreement (221150) between Perimetrics, Inc and the University of California, Irvine.

The authors gratefully acknowledge MSC software, a division of Hexagon Inc, for providing licenses to use the Marc and Apex software, and extend their thanks to Doug Malcolm of MSC Software and Dr David Dimas at the University of California, Irvine. The 3-dimensional tooth geometries used in this study were generously provided by eHuman, Inc, and the authors are indebted to Drs Eric Herbranson, Bao Pham, and Kevin Montgomery for their assistance in acquiring these geometries. The authors acknowledge Jennine Cszimas for contributing her design expertise in creating the graphical abstract.

ORCID Number. Jie Shen <https://orcid.org/0009-0007-1922-4572>. For information regarding ORCID numbers, go to <http://orcid.org>.

References

1. Stashenko P, Yu SM, Wang CY. Kinetics of immune cell and bone resorptive responses to endodontic infections. *J Endod.* 1992;18(9):422-426. doi:10.1016/S0099-2399(06)80841-1
2. Storrer CM, Bordin GM, Pereira TT. How to diagnose and treat periodontal-endodontic lesions? *RSBO Rev Sul-Bras Odontol.* 2012;9(4):427-433. doi:10.21726/rsbo.v22i1
3. Evans M. The endodontic-periodontal juncture: where two worlds meet—an overview of endo-perio lesions. *Aust Dent J.* 2023;68(suppl 1):S56-S65. doi:10.1111/adj.12993
4. Oktawati S, Siswanto H, Mardiana A, Supiaty NI, Neormansyah I, Basir I. Endodontic-periodontic lesion management: a systematic review. *Med Clin Pract.* 2020;3, 100098. doi:10.1016/j.mcpsp.2020.100098
5. Salvi GE, Rocuzzo A, Imber JC, Stähli A, Klinge B, Lang NP. Clinical periodontal diagnosis. *Periodontol* 2000. Published online July 14, 2023. doi:10.1111/prd.12487
6. Sheets CG, Hui DD, Bajaj V, Earthman JC. Quantitative percussion diagnostics and bone density analysis of the implant-bone interface in a pre- and postmortem human subject. *Int J Oral Maxillofac Implants.* 2013;28(6):1581-1588. doi:10.11607/jomi.3037
7. Dinh A, Sheets CG, Earthman JC. Analysis of percussion response of dental implants: an in vitro study. *Mater Sci Eng C Mater Biol Appl.* 2013;33(5):2657-2663. doi:10.1016/j.msec.2013.02.033
8. Sheets CG, Stewart DL, Wu JC, Earthman JC. An in vitro comparison of quantitative percussion diagnostics with a standard technique for determining the presence of cracks in natural teeth. *J Prosthet Dent.* 2014;112(2):267-275. doi:10.1016/j.prosdent.2014.02.020
9. Sheets CG, Wu JC, Rashad S, Phelan M, Earthman JC. In vivo study of the effectiveness of quantitative percussion diagnostics as an indicator of the level of the structural pathology of teeth. *J Prosthet Dent.* 2016;116(2):191-199.e1. doi:10.1016/j.prosdent.2016.01.015
10. Sheets CG, Wu JC, Rashad S, Phelan M, Earthman JC. In vivo study of the effectiveness of quantitative percussion diagnostics as an indicator of the level of structural pathology of teeth after restoration. *J Prosthet Dent.* 2017;117(2):218-225. doi:10.1016/j.prosdent.2016.07.010
11. Sheets CG, Zhang L, Wu JC, Earthman JC. Ten-year retrospective study of the effectiveness of quantitative percussion diagnostics as an indicator of the level of structural pathology in teeth. *J Prosthet Dent.* 2020;123(5):693-700. doi:10.1016/j.prosdent.2019.05.028
12. Sheets CG, Quan DA, Wu JC, Earthman JC. An evaluation of quantitative percussion diagnostics for determining the probability of a microgap defect in restored and unrestored teeth: a prospective clinical study. *J Prosthet Dent.* 2025;133(3):756-763. doi:10.1016/j.prosdent.2023.04.016
13. Shen J, Taheri-Nassaj N, Sheets CG, Earthman JC. Finite element modeling of an intact and cracked mandibular second molar under quantitative percussion diagnostics loading. *J Prosthet Dent.* 2024;132(3). doi:10.1016/j.prosdent.2024.09.003. S0022-3913(24)00601-2.
14. Mapar A, Taheri-Nassaj N, Shen J, Komari O, Sheets CG, Earthman JC. Finite element study of periodontal ligament properties for a maxillary central incisor and a mandibular second molar under percussion conditions. *J Med Biol Eng.* 2022;42(5):681-691. doi:10.1007/s40846-022-00724-5
15. Nalla RK, Imbeni V, Kinney JH, Staninec M, Marshall SJ, Ritchie RO. In vitro fatigue behavior of human dentin with implications for life prediction. *J Biomed Mater Res A.* 2003;66(1):10-20. doi:10.1002/jbm.a.10553
16. Reeh ES, Messer HH, Douglas WH. Reduction in tooth stiffness as a result of endodontic and restorative procedures. *J Endod.* 1989;15(11):512-516. doi:10.1016/S0099-2399(89)80191-8
17. Mannocci F, Cowie J. Restoration of endodontically treated teeth. *Br Dent J.* 2014;216(6):341-346. doi:10.1038/sj.bdj.2014.198
18. O'Brien WJ. *Dental Materials and Their Selection.* 2nd ed. Quintessence Publishing; 1997.
19. Poppe M, Bourauel C, Jäger A. Determination of the elasticity parameters of the human periodontal ligament and the location of the center of resistance of single-rooted teeth: a study of autopsy specimens and their conversion into finite element models. *J Orofac Orthop.* 2002;63(5):358-370. doi:10.1007/s00056-002-0067-8
20. Fill TS, Carey JP, Toogood RW, Major PW. Experimentally determined mechanical properties of, and models for, the periodontal ligament: critical review of current literature. *J Dent Biomech.* 2011;2011, 312980. doi:10.4061/2011/312980
21. Dhammayannarangi P, Na Lampang S, Tompkins KA, et al. Using the appropriate modulus of elasticity of periodontal ligament matters in stress analysis of human first premolar tooth and periodontium structures. *Sci Rep.* 2025;15(1):1549. doi:10.1038/s41598-025-85578-y