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THE JOURNAL OF PROSTHETIC DENTISTRY

CLINICAL RESEARCH

# In vivo study of the effectiveness of quantitative percussion diagnostics as an indicator of the level of the structural pathology of teeth

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## ABSTRACT

**Statement of problem.** Conventional dental diagnostic aids based upon imagery and patient symptoms are at best only partially effective for the detection of fine structural defects such as cracks in teeth.

**Purpose.** The purpose of this clinical study was to determine whether quantitative percussion diagnostics (QPD) provided knowledge of the structural instability of teeth before restorative work begins. QPD is a mechanics-based methodology that tests the structural integrity of teeth noninvasively.

**Material and methods.** Eight human participants with 60 sites needing restoration were enrolled in an institutional review board-approved clinical study. Comprehensive examinations were performed in each human participant, including QPD testing. Each site was disassembled and microscopically video documented, and the results were recorded on a defect assessment sheet. Each restored site was then tested using QPD. The normal fit error (NFE), which corresponds to the localized defect severity, was correlated with any pretreatment structural pathology.

**Results.** QPD agreed with clinical disassembly in 55 of 60 comparisons (92% agreement). Moreover, the method achieved 98% specificity and 100% sensitivity for detecting structural pathologies found later upon clinical disassembly. Overall, the NFE was found to be highly predictive of advanced structural pathology.

**Conclusions.** The data from the present in vivo study support the hypothesis that QPD can provide the clinician with advance knowledge of the structural instability of teeth before restorative work begins. (J Prosthet Dent 2016;116:191-199)

Clinical dentistry has been limited by a lack of diagnostic tools that detect microscopic and/or hidden defects. These defects can manifest additional instability during function in unrestored or restored teeth and implants. In the natural dentition, breakdown beneath radiopaque restorations, cracks that are within the dentin, or other common conditions related to structural integrity cannot be detected.[1,2]

Most clinical diagnostic aids are based upon visual inspection and subjective patient symptoms.[3,4] Visualization of a crack can be enhanced by transillumination with a fiber optic light, use of a dye penetrant, and magnification.[5-8] Methods used to reproduce a patient's symptoms include percussion, occlusal testing, and thermal pulp testing.[9] The occlusal test has been described as the most reliable of clinical tests to reproduce symptoms.[10] Unfortunately, by the time "cracked tooth" symptoms have developed, the pulpal tissues of the tooth are irritated and the crack is in a more advanced stage of structural breakdown.[11]

Detecting a crack from a radiograph is generally very difficult, if not impossible.[12] The crack must be separated,

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## Clinical Implications

A new mechanics-based diagnostic technology, quantitative percussion diagnostics (QPD), can provide information on the structural integrity of natural teeth. Higher normal fit error (NFE) values correlate with more severe levels of structural pathology. If NFE values are available early, therapeutic or preventive therapies can minimize further breakdown. Accordingly, QPD provides useful risk assessment data that cannot be obtained using conventional dental diagnostics.

in the same plane as the radiation beam and/or have created bone loss at the site of the fracture to be captured as a radiographic feature. Additionally, numerous documented studies show minimal agreement among clinicians on the interpretation of radiographic results.[13,14]

Other imaging techniques are being developed to help visualize cracks, such as monostatic pulse-echo ultrasound,[15] optical coherence tomography,[16] swept-source optical coherence tomography,[17] vibrothermography,[18] and a laser ultrasonic system.[19] Each of these technologies develops visual images representing the crack defect, but all are limited in the quality of results and extent of research to date. None has been the subject of published in vivo testing or clinical trials. The greatest limitation is that they rely on visual images. None is able to determine the effect of the visualized crack under normal masticatory and parafunctional loading.

Structural integrity in engineering is generally assessed in a more direct manner.[20] Ideally, specimens are tested under conditions that are relevant to service and provide a direct measurement of mechanical response. In the mouth, testing for structural integrity should be consistent with dynamic loading during mastication and parafunction.

Quantitative percussion diagnostics (QPD) is a mechanics-based methodology that has been used clinically to analyze the structural integrity of teeth and dental implants. Studies have demonstrated the capabilities of QPD to determine the quality of implant osseointegration during any phase of treatment.[20-22] A recent in vitro study has shown that QPD can be highly sensitive for detecting the presence of cracks and fractures in natural teeth.[23] In these studies, 2 parameters were evaluated for each specimen using QPD, the loss coefficient (LC) and the normalized fit error (NFE). LC characterizes the overall mobility of the site, and NFE indicates the degree of local instabilities such as cracks in the site. The explanation for determining the LC is given elsewhere.[22,23] These parameters are determined automatically in a computer for each QPD test by analyzing the measured mechanical energy generated as a function of time. This response, plotted as energy return versus time, that is, energy return graph, can be useful for illustrating the overall and localized stability of a given site.[22-24] A description of how the NFE is determined during QPD is given in Supplemental Material.

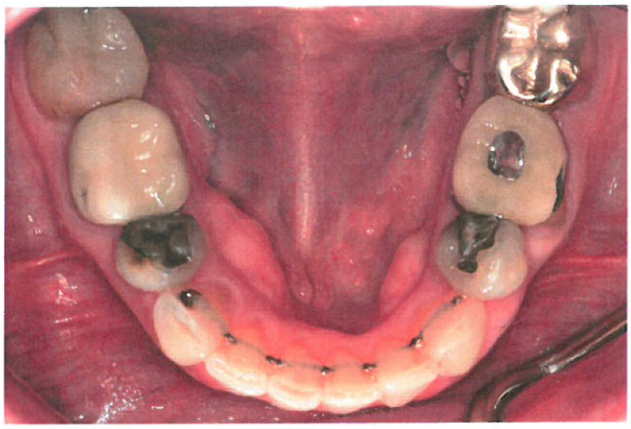

Figure 1. Pretreatment occlusal view of mandibular arch for participant F.

The present study examined the ability of QPD to provide the clinician with information for the structural health of a tooth before treatment. In particular, it focused on the ability of the NFE to indicate the pretreatment structural stability of the sites that will be restored. The study hypothesis was that QPD provides knowledge of the structural instability of teeth before restorative treatment begins.

## MATERIAL AND METHODS

Eight human participants scheduled for restorative treatment were given a QPD complete mouth evaluation pretreatment for a total of 60 sites included in the study. Each site was disassembled using a microscope at ×8 to ×14 magnification (Global Surgical), using dye penetrant (toluidine Blue O indicator; Taylor Technologies) and a transillumination wand (TI2200; Kerr Dental) as described in a previous report.[24] The term "disassembled" refers to the removal of any restorations, bases, damaged enamel, diseased tooth structure, or tooth structure removed for the creation of space for restorative materials. This procedure allowed for a comprehensive visual assessment of structural pathology, even to the pulp chamber when appropriate. In addition, two independent evaluators examined the radiographs for pretreatment pathology, and patient-reported symptoms were documented. Finally, clinical data findings were compared with the NFE data sets.

Participants were selected within a private prosthodontic practice from patients scheduled for normal restorative care, ranging from a single crown to complete

mouth reconstructive treatment. Figure 1 shows a representative example of a mandibular arch where each tooth required restorative treatment. The 60 sites diagnosed for restorative care included failing restorations, symptoms of a cracked tooth, wear, need for occlusal refinement, poor esthetics, or other issues. This number of sites for the present study was based on the statistically significant sample size from a previous in vitro study of cracks in extracted natural teeth.[24] The following conventional comprehensive examination techniques were used to determine each participant's need for restorative services: complete mouth radiographs, periodontal evaluation, oral cancer screening, occlusal/temporomandibular joint evaluation, dental examination, and diagnostic photographs and casts. All participants met the inclusion/exclusion criteria and signed informed consents, and institutional review board-approved protocols were followed.

QPD was performed using a percussion probe diagnostic instrument (Periometer; Perimetrics LLC) that records and analyzes the percussion response of teeth. The results were kept in a sealed file that was not accessible to the treating clinician (C.G.S.). During the restorative appointments, clinical procedures were videotaped through a clinical microscope, and findings such as microleakage, recurrent caries, incomplete or complete fractures, location and size of any fractures or other structural weaknesses were charted on a written Dental Assessment Tool (DAT) (Fig. 2). Two nontreating examiners independently rated each site's radiographs for pathology, without benefit of a visual examination. Each site was prepared for appropriate tooth preparations, impression capture, and interim restoration. Any teeth requiring follow-up procedures, such as endodontic treatment or extractions, were appointed for treatment, and the results were fully documented. Normal maintenance was provided during the interim restoration. The definitive restorations were evaluated, approved by the participant for delivery, and cemented with an appropriate luting agent. Information from the DAT sheets, the video documentation, and the subsequent treatment progress notes ("clinical documentation") were used in the analysis of each site.

To address the prognostic value of NFE for the clinical pathology of a site, a cumulative logistic regression model[25] was fitted for the probability of the pathology classification based on the NFE values. The model was used to quantify the strength of association between NFE values and the clinical pathology of the site and to quantify the predictive capability of NFE as a prognostic clinical tool. Next, a classification and regression tree was fitted[26] to construct a diagnostic decision tree for the classification and prediction of pathology from NFE values. Here a set of 3 cutoff values were determined that divided NFE into 4 ranges of values corresponding to a classification of a dental site into 1 of the 4 pathology ratings. The model was then represented by a classification or decision tree, where the final cutoffs were chosen so as to minimize the sample fraction of misclassified sites. These analyses were completed using the programming environment R.[27]

## RESULTS

Based upon clinical findings, the 60 sites were divided into 4 categories: no pathology, mild pathology, moderate pathology, and severe pathology. Table 1 provides typical findings for these 4 categories. No pathology refers to a site with total structural health and no significant defects. Mild pathology was designated when minor defects such as enamel cracks were observed. Moderate pathology was defined as initial structural breakdown from caries, dentinal cracks, or other mild to moderate irreversible breakdown. Severe pathology was determined for sites where a clinician would want to take immediate corrective action. Figure 3 shows all 60 sites in a bar graph, rated and color coded by the examiner to represent the degree of structural pathology. Sixteen sites were classified with severe pathology, 13 with moderate pathology, 11 with mild pathology, and 20 with no pathology.

Figure 4 illustrates the frequency of reported patient symptoms in the 60 sites and the presence or absence of radiographic evidence of pathology as noted by 2 independent reviews. Only 4 sites indicated that the participant had reported any pretreatment symptoms, and all 4 of these sites were classified as having severe pathology upon disassembly. Four different sites were determined to have radiographic signs of compromised structure as mutually identified by both radiograph examiners. Upon disassembly, none of these sites exhibited severe pathology, 1 was found to have moderate pathology, 2 exhibited mild pathology, and 1 had no pathology. This site, B7, was not symptomatic and was identified by both radiograph examiners as likely having a widened periodontal ligament, even though later disassembly revealed no internal structural pathology. Eight more sites were identified by 1 of the 2 independent examiners as having radiographic indications of compromised tooth structure. Of these additional 8 sites, 2 were found to exhibit severe pathology during disassembly, 1 was found to contain moderate pathology, 1 exhibited mild pathology, and 4 had no pathology (Fig. 4). This disagreement between radiographic interpretation and direct observations of structural pathology during disassembly is consistent with previous studies on the level of effectiveness of interpretation of radiographic data in dentistry.[13,14]

The NFE from QPD testing was also examined for each site as it corresponds to localized defects that are contained in or are adjacent to the tooth being tested. All

| Study Protocol # | | | | Protocol # | | | | Facility identifier/ Subject # | | | | | Subject Initials | | | | Date Month/Day/Year | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 1 | - | 1 | 0 | 2 | - | 2 | 0 | | | | | | | | | | |

**TESTING SITE#_____CONDITION CHECKLIST**

Indicate whether or not there is a presence of the conditions listed below

1. Microleakage/Cement Loss:
   ☐ None ☐ Leakage
2. Decay:
   ☐ None ☐ Mild ☐ Moderate ☐ Severe
3. Oblique Cuspal Incomplete Dentinal Fractures:
   ☐ None ☐ 1 Cusp ☐ 2 Cusps ☐ 3 Cusps ☐ 4 Cusps
4. Vertical Incomplete Dentinal Fractures (Cavity Preparation Floor)
   ☐ None ☐ Mild ☐ Moderate ☐ Severe
5. Incomplete Fractures of Pulp Chamber Floor (Furcal Floor)
   ☐ None ☐ Severe ☐ Unable to Determine
6. Bone Loss – Periodontal:
   ☐ None ☐ Mild ☐ Moderate ☐ Severe ☐ Terminal
7. Bone Loss - Endodontic
   ☐ None ☐ Mild ☐ Moderate ☐ Severe
8. Widened Periodontal Ligament Space
   ☐ None ☐ Yes
9. Other (loose D/C, traumatic accident, etc.)
   ☐ None ☐ Yes

Describe:_____

_____

_____

Loss Coefficient:_____ Mean Fit Error:_____

X-ray defects present: YES NO Symptoms: YES NO

X-ray 2nd Opinion: YES NO

**Figure 2.** Dental Assessment Tool sheet for written record of visual findings.

60 NFE results were included in a bar chart by site number as shown in Figure 5. Values are based on a computer-generated quantitative analysis of mechanical response data as described in Supplemental Material.[22-24] Each NFE pathology score was also color-coded to represent the clinical categorization of the pathology determined from the subsequent disassembly observation also plotted in Figure 3.

Figure 6 takes the same NFE data shown in Figure 5 and reconfigures the sites along the horizontal axis from the lowest to highest NFE, still color-coded to represent the clinically assigned severity of structural pathology. Five sites exhibited a difference between the clinical visual assessment and the mechanical NFE ranking. These were sites C31 (green), F8 and F9 (yellow), and F7 and F10 (orange).

Clinical notes revealed that site C31 had a class I alloy with slight marginal leakage. The restoration was small, and no dentinal fractures were found with the clinical microscope, dye penetrant, and transillumination. The site had a very high NFE, indicating severe pathological micromovement. Accordingly, this outcome either

**Table 1.** Typical findings for four categories of structural breakdown: no, mild, moderate, and severe

| No Pathology - Green | Mild Pathology - Yellow |
|---|---|
| • Intact enamel<br>• Periodontally stable<br>• None or incipient decay<br>• No incomplete fractures | • Intact or predominantly intact enamel<br>• Mild microleakage<br>• Mild incipient decay<br>• Minimal incomplete fractures<br>• Mild bone loss<br>• Mild widened ligament space |
| **Moderate Pathology - Orange** | **Severe Pathology - Red** |
| • Moderate microleakage<br>• Moderate decay<br>• Incomplete fractures<br>• Widened ligament spaces<br>• Additional structural breakdown | • Severe microleakage<br>• Moderate to severe decay<br>• Severe, often multiple incomplete fractures<br>• Moderate and severe bone loss<br>• Severe widened ligament spaces<br>• Additional structural breakdown<br>• Pain |

corresponds to a QPD false positive or a significant defect still in the structure that was not observed during disassembly. Defects could still exist in nonvisible areas, such as the root, as was shown in an in vitro study.[24]

Both sites F8 and F9 had mobility after orthodontic treatment, with a significantly widened periodontal ligament. On disassembly, the tooth structure exhibited no significant damage. The mild bone damage induced by orthodontic treatment created the pathological micromovement measured for each of these sites. Sites F7 and F10 had histories similar to those of sites F8 and F9 but demonstrated more mobility after orthodontic treatment and greater widening of the periodontal ligament radiographically.

Table 2 lists the associated statistics from the experimental data for a confidence level of 95%. These results show that 55 of 60 teeth (92%) were ranked consistently between QPD and clinical microscopic disassembly (95% confidence interval [CI]: 0.819-0.964) for this proportion. We noted only 5 false positive and no false negatives. Accordingly, the results indicate at least 92% overall specificity (95% CI: 0.911-0.997) and 100% sensitivity (95% CI: 0.940-1.000) for detecting structural pathology that was later found during clinical microscopic disassembly.[25]

The frequency distribution of the clinical pathology ratings is shown in Table 3, where the count unit was the participant site for a total of 60 observations. Summaries of the distribution of NFE values ($\times 10^2$) are shown in Table 4, where median and IQR (interquartile range) were tabulated by pathology rating. Median NFE increased with the pathology rating. The classes were separated by approximately 0.0089 units, which corresponded to approximately 1 standard deviation (SD) among nonpathological sites. The distribution of NFE values are also plotted in Figures 7 and 8. Figure 7 shows mean NFE values with ±1 SD by pathology rating, whereas Figure 8 shows boxplots of NFE values. Good separation was observed among the 4 rating classes, suggesting that a classifier based on NFE values would prove strongly predictive. One exception may be the noted overlap of NFE values for ratings "Mild" and "Moderate." The pathology rating "Severe" showed the greatest separation of NFE values, where the variability was also larger than that found within all other clinical ratings.

To address the predictive value of NFE, a cumulative logistic regression model was fitted for the probability of each pathology rating based on NFE values. Although dental sites were clustered within patients, they were treated as independent in the model because the intrapatient correlation was found to be negligible (estimated intrapatient correlation = $5.8\times10^{-9}$). Model summaries are shown in Table 5, and the analysis of variance (ANOVA) is shown in Table 6. Based on a chi-square test

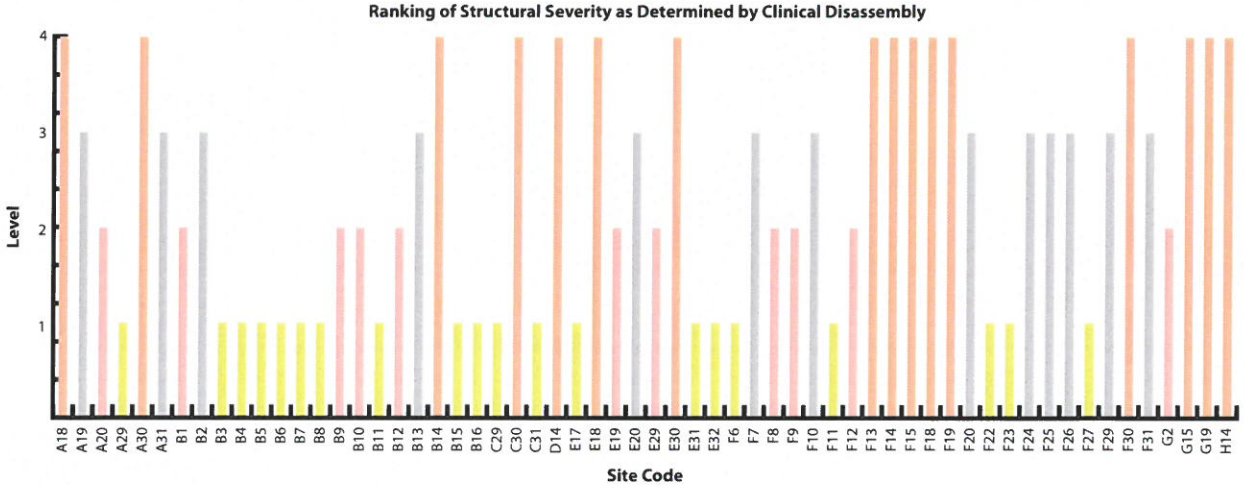


**Figure 3.** Bar chart with all 60 sites rated as to severity of structural defects as determined by disassembly process: 1, green = no pathology; 2, pink = mild pathology; 3, gray = moderate pathology; 4, orange = severe pathology.

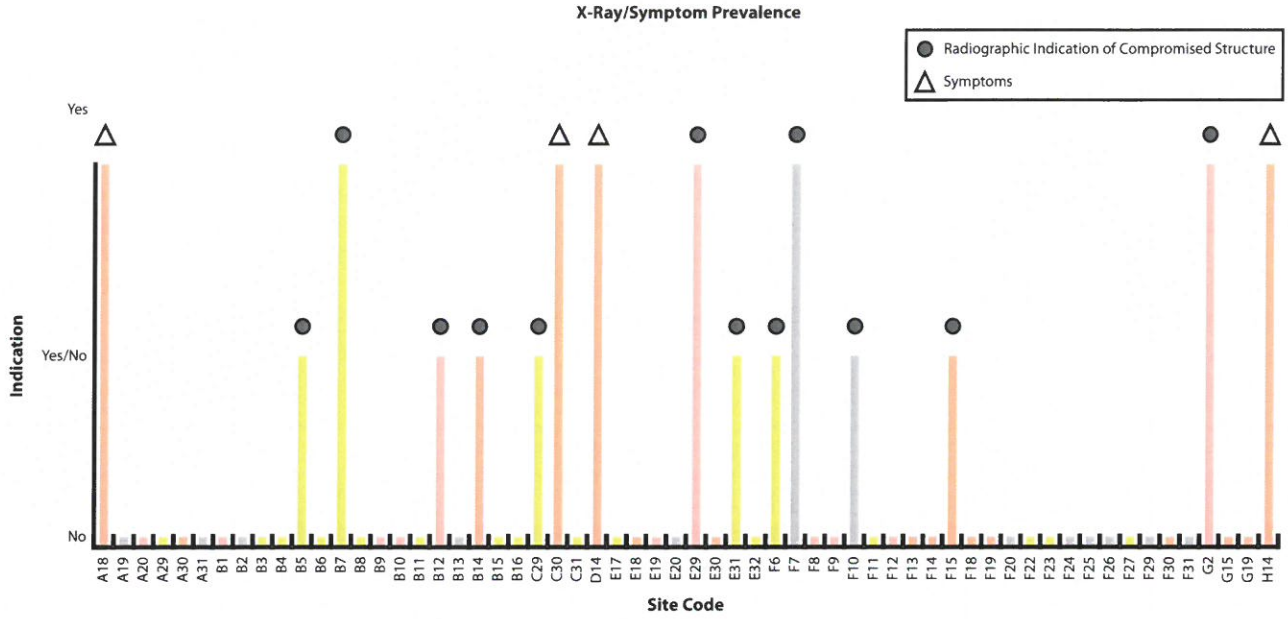


**Figure 4.** Sites that exhibited radiographic indications of structural breakdown according to 2 dental examiners or 1 of 2 dental examiners. Also, sites associated with participant-reported symptoms. Color designation of site is clinical disassembly rating.

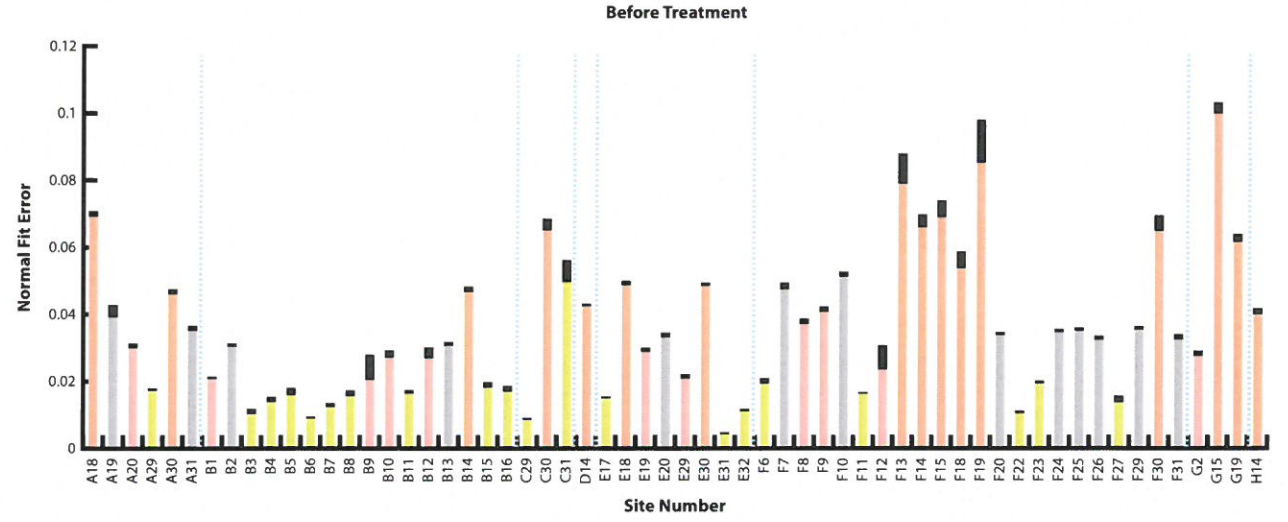


**Figure 5.** Pretreatment NFE results for 60 sites in study show range from no (green), mild (pink), moderate (gray), to severe (orange) structural pathology. Black bar above each color-coded column represents standard deviation. NFE, normal fit error.

with 1 degree of freedom, the predictive value of NFE for clinical rating was strongly significant (chi-square=93.02, DF=1; $P<.001$). Also, for each SD (0.0089) increase in NFE values, the odds of a higher clinical rating was 11.92 times the odds of a lower clinical rating (odds ratio=11.92; 95% CI: 7.58-18.74; $P<.001$). Thus, given NFE values of 2 sites, the site with the greater NFE value was strongly associated with the higher pathology rating.

The regression model provided estimates of the probability of each clinical rating as a function of NFE values. Each rating corresponds to a single curve as plotted in Figure 9. To classify the pathology of a site based on NFE value, a simple rule would assign the pathology with the highest probability using the empirical NFE threshold values 0.0223, 0.0311, and 0.044. These values are predictively associated with a particular pathology rating based on the highest of the 4 probability curves in each section of the graph. An NFE value greater than 0.044, for example, was most likely to be pathologically severe.

An optimal set of NFE-cutoffs is shown in Figure 10, where a tree was graphed of the resulting classification

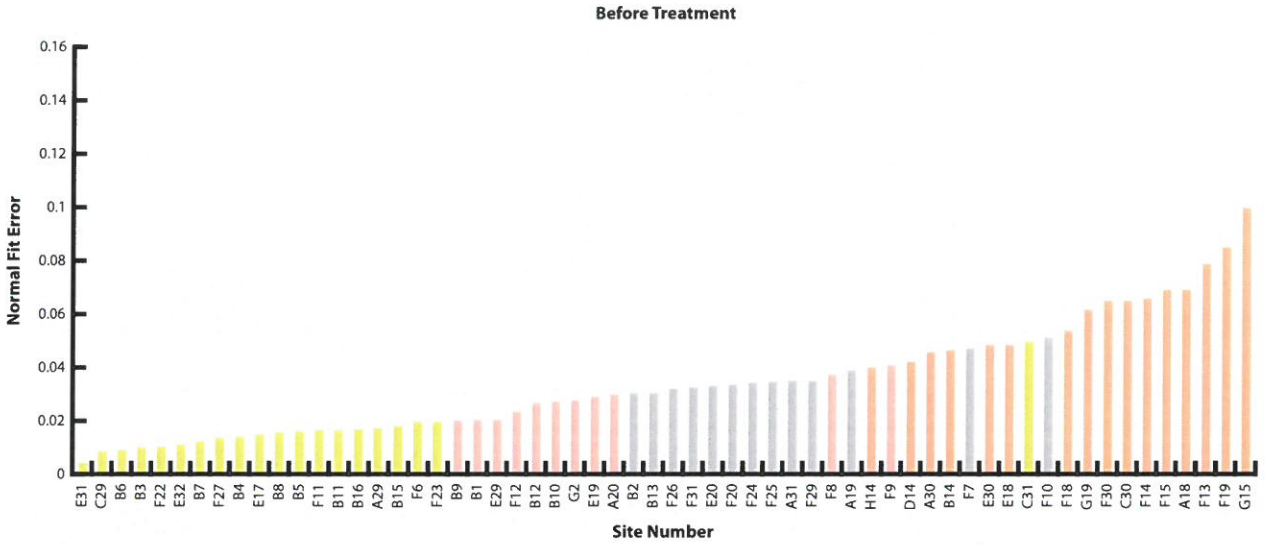


Figure 6. Mean NFE values (color-coded columns) plotted in ranked order against structural pathology level. NFE, normal fit error.

Table 2. Associated statistics from experimental data indicating

| Statistic | Proportion | 95% CI |
|---|---|---|
| Proportion correctly classified | 55/60=0.9167 | 0.8194-0.9639 |
| Positive predictive value | 59/60=0.9833 | 0.9114-0.997 |
| Negative predictive value | 60/60=1.0000 | 0.9398-1.0000 |
| Sensitivity | 60/60=1.0000 | 0.9398-1.0000 |
| Specificity | 59/60=0.9833 | 0.9114-0.997 |
| False-positive rate | 1/60=0.0167 | 0.0009-0.1014 |
| False-negative rate | 0/60=0.0000 | 0.0000-0.0602 |

Table 3. Distribution of patient sites by clinical pathology

| | None | Mild | Moderate | Severe |
|---|---|---|---|---|
| Count | 20 | 11 | 13 | 16 |
| Fraction | 0.33 | 0.18 | 0.22 | 0.27 |

rule. Note that the optimal thresholds agreed quite closely with those indicated in Figure 8 as based on maximizing local classification probability. To use the tree, note that each node splits the dental sites into groups based on NFE values. One enters the root of the tree with the NFE value of a site and follows the branches of the tree based on the cutoff values, namely 0.0199, 0.0302, and 0.0397, until a pathology rating is reached at the corresponding leaf. The performance of the tree was judged by the sample fraction of misclassified sites, and the optimal cutoffs were chosen to minimize the misclassification rate. An NFE value of 0.04 would reach the leaf labeled "Severe," for example, where a total of 20 sites were classified with NFE values >0.0397. Of these 20 sites, there were 1, 1, 2, and 16 sites having clinical ratings of "None," "Mild," "Moderate," and "Severe," respectively, so that a total of 4 sites were misclassified at that leaf. To understand the performance of the NFE classifier, note that ignoring NFE values resulted in a misclassification rate of 40/60 or 66.7%, whereas classification based on NFE threshold values resulted in a misclassification rate of only 5/60 or 8.3%. To adjust for overfitting in the sample, an estimate of the performance of the tree was also based on 10-fold cross-validation. Here the error rate was estimated to be 19/60 or 31.7%. The cross-validated rate estimates the misclassification rate to be expected when using the decision tree with new data that were sampled in the same way as the present data. As noted in the Discussion, the most challenging classification was separating mildly from moderately rated sites.

## DISCUSSION

A common frustration among dentists is to discover undiagnosed dental disease because of the limitations of the traditional diagnostic armamentarium. For decades, visual diagnostics and a thorough patient history have been the gold standard for comprehensive examinations. Although these tools are essential for detecting much dental disease, they are not adequate for detecting cracks in teeth, structural mechanical defects, or breakdown under radiopaque restorations until late in the disease process.

The 92% rate of agreement between NFE level and structural pathology observed during disassembly supports the hypothesis that QPD provides predictive advance knowledge of structural instability of teeth before restorative work. Mechanical testing more closely correlated with the disassembly results than radiographic evidence or patient symptoms. The specificity (98%) and sensitivity (100%) results are in excellent agreement with those obtained in a recent in vitro study of crack detection using the NFE, 96% and 100%, respectively.[24] The

**Table 4.** NFE values by clinical pathology

| None (n=20) | Mild (n=11) | Moderate (n=13) | Severe (n=16) |
|---|---|---|---|
| NFE →102 1.53 (1.09-1.71) | 2.72 (2.22-2.95) | 3.45 (3.26-3.54) | 6.33 (4.75-6.90) |

NFE, normal fit error. Data show NFE values by clinical pathology, reporting median and interquartile range (IQR). Unit is patient site.

**Table 5.** Cumulative logistic regression model for probability of clinical pathology rating based on NFE values

| Factor | Coeffficient (95% CI) | *P* | n |
|---|---|---|---|
| Rating constants | | | |
| None—mild | 6.05 (4.85-7.25) | <.001 | 60 |
| Mild—moderate | 8.74 (7.12-10.37) | <.001 | 60 |
| Moderate—severe | 12.31 (10.11-14.50) | <.001 | 60 |
| Per SD (0.0089 unit) increase | | | |
| NFE | 11.92 (7.58-18.74) | <.001 | 60 |

NFE, normal fit error; SD, standard deviation. Rating constants are shown on logit scale. Odds ratio of higher versus lower pathology rating was calculated for approximately 1 SD unit increase in NFE value. SD was calculated for sites within nonpathological sites.

**Table 6.** Likelihood ratio test of rating model based on NFE

| | Model | Resid. *df* | -2logLik | Test | Df | LR stat | Pr(Chi) |
|---|---|---|---|---|---|---|---|
| 1 | Null | 57 | 163.33 | | | | |
| 2 | NFE | 56 | 70.31 | 1 vs 2 | 1 | 93.02 | <.001 |

−2logLik, minus 2 times the log likelihood; LR stat, likelihood ratio test statistic; NFE, normal fit error; Pr(Chi), *P* value for the chi-squared test; Resid. *df*, number of independent data points; Df, degrees of freedom of the test.

fact that only false positives were registered leaves open the possibility they may be due to cracks that were missed during the disassembly procedure as opposed to an erroneously high NFE value. The clinical notes from pretreatment disassembly were in basic agreement with the increasing NFE scores.

Two factors limited the performance of the present classification tree shown in Figure 10. First, it was based on a small sample of 8 participants, although the participants were representatively sampled and they contributed a total of 60 sites. Second, considerable overlap was observed in NFE values for the "Mild" and "Moderate" ratings, so that separating these 2 groups proved the least reliable in cross-validation. In future research, we propose that the classification rule be tested on an independent sample of approximately 10 to 15 participants, each contributing approximately 7 or 8 sites. This would allow an out-of-sample validation of the rule, and, if necessary, a recalibration of the decision tree.

## CONCLUSIONS

The present study data show that QPD was able to provide strongly predictive advance knowledge of structural instabilities of teeth before restorative treatment. The establishment of baseline structural stability for each patient before treatment provides a new risk assessment tool, a patient educational tool, and a motivator for preventive compliance. Mechanical testing provides

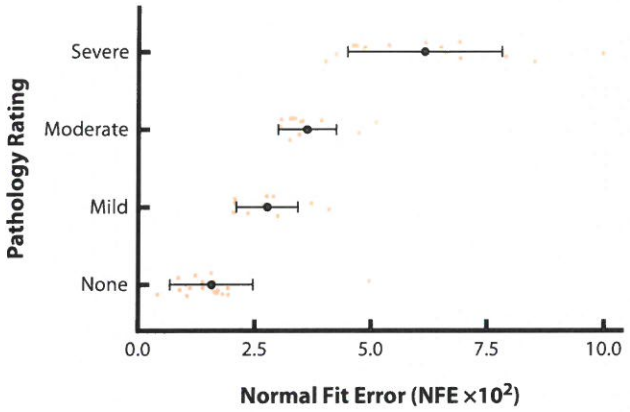


**Figure 7.** Distribution of NFE values by pathology rating. Unit is patient site. Spread of NFE values by pathology rating. Error bars show mean NFE value ±standard deviation. NFE, normal fit error.

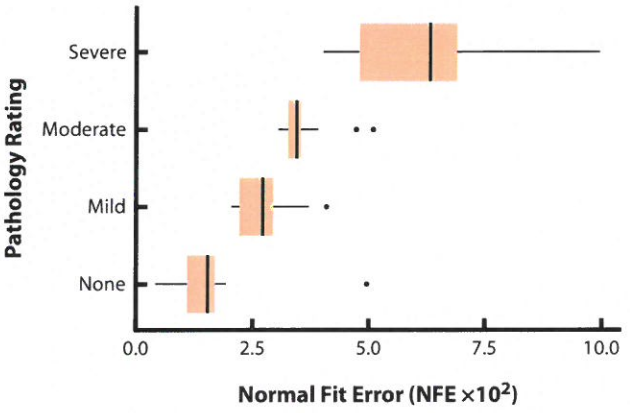


**Figure 8.** Boxplots of NFE values by pathology rating. Boxes bound range of middle fifty percent of each sample. Distributions were separated by pathology rating, with steady increase in NFE values. Greater variability was observed in severe rating. Outliers (circular points) were noted at rating none, mild, and moderate, and all were greater than respective means. NFE, normal fit error.

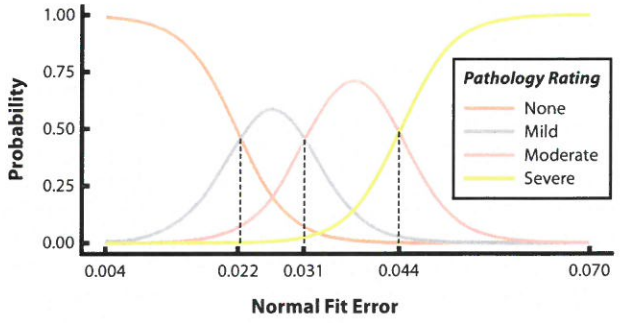


**Figure 9.** Probability curves for pathology rating based on NFE values. Rating splits based on NFE values are shown where probability of higher rating exceeds probability of lower rating. NFE, normal fit error.

clinicians a technology to evaluate biomechanical integrity of restored and unrestored teeth. Further research is indicated to test the limits of information provided by this

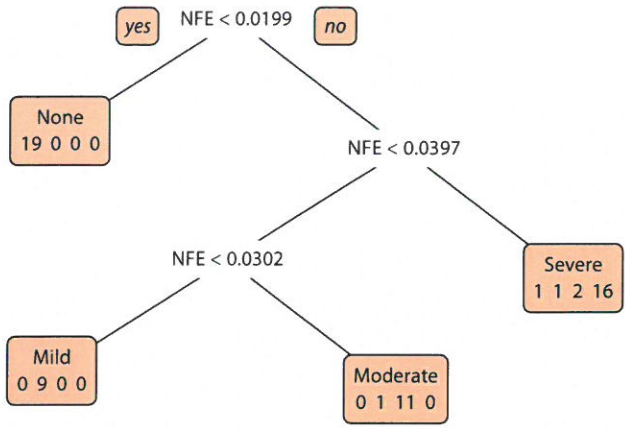


**Figure 10.** Classification tree based on NFE value. Optimal cutoffs minimized probability of misclassification across tree. NFE, normal fit error.

new diagnostic paradigm in follow-up, post-treatment assessments.

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## SUPPLEMENTAL MATERIAL

The force variation resulting from periometer percussion is determined by a sensor in the hand piece.[1] The energy return, $E_r$, characterizes the elastic energy of this force according to

$$E_r = \frac{F^2}{2K}, \tag{S1}$$

where $F$ is the resultant percussion force and $k$ is the stiffness of the percussion rod assembly. The normalized energy return, $\bar{E}_r$, is the energy return during impact divided by the kinetic energy of the percussion rod just before impact with the sample. The energy return/impact energy variation for a defect-free calibration sample could be expressed in the form:

$$\bar{E}_r = \beta \sin^2(\gamma t) \exp\left[-\frac{(t-\phi)^2}{\psi}\right], \tag{S2}$$

where $t$ is time and $\beta$, $\gamma$, $\phi$, and $\psi$ are parameters determined by the best fit to the experimental data.

A nonlinear regression fit of Equation S2 to 10 energy return data sets was performed for each implant model in the present study, using the Levenberg-Marquardt algorithm.[2] The resulting mean residue, weighted mean error of the fitted model to all 10 data sets, was divided by the overall amplitude of the data to obtain a normalized fit error. This normalization of the mean fit error with the amplitude is justified by the observation that defects have a greater effect on distorting energy return peaks that have higher amplitudes. A greater distortion in the mechanical response results is also reasonable when more energy is available to drive the localized movements associated with a localized defect.

## SUPPLEMENTAL REFERENCES

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