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RESEARCH AND EDUCATION

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

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ABSTRACT

Statement of problem. Conventional diagnostic aids based upon imagery and patient symptoms do not indicate whether restorative treatments have eliminated structural pathology.

Purpose. The purpose of this clinical study was to evaluate quantitative percussion diagnostics (QPD), a mechanics-based methodology that tests the structural integrity of teeth noninvasively. The study hypothesis was that QPD would provide knowledge of the structural instability of teeth after restorative work.

Material and methods. Eight participants with 60 sites needing restoration were enrolled in an IRB-approved clinical study. Each participant was examined comprehensively, including QPD testing. Each site was disassembled and microscopically video documented, and the results were recorded on a defect assessment sheet. A predictive model was developed for the pathology rating based on normalized fit error (NFE) values using data from the before treatment phase of the study published previously. Each restored site was then tested using QPD. The mean change in NFE values after restoration was evaluated by the pathology rating before treatment. The model was then used to predictively classify the rating after restoration based on the NFE values after treatment. The diagnostic potential of the rating was explored as a marker for risk of pathology after restoration.

Results. After restoration, 51 of the 60 sites fell below an NFE of 0.04, representing a greatly stabilized tooth site sample group. Several sites remained in the high-risk category and some increased in pathologic micromovement. Two models were used to determine severity with indicative cutoff points to group sites with similar values.

Conclusions. The data support the hypothesis that QPD can indicate a revised level of structural instability of teeth after restoration. (J Prosthet Dent 2016;■:■-■)

Patients often feel that their restored teeth are as structurally sound as defect-free natural teeth (Fig. 1). However, even a precisely restored tooth may have residual structural instability. Furthermore, the structural foundation under similar looking restored teeth can differ drastically. There may be remaining dentinal cracks, dentinal loss due to endodontic therapy, extensive use of foundation materials, significant reduction of tooth structure for complete coverage restorations, or other necessary but structurally weakening therapeutic interventions. When differing support mechanisms such as natural teeth or dental implants are combined with multiple restorative solutions and materials, biomechanical issues may become problematic.[1,2] Therefore, varying structural stabilities and biomechanical complications can exist in a single mouth.

Identifying high-risk teeth in patients after restoration would provide clinicians critical information for future oral health maintenance. This information would also provide patients a more realistic expectation of the

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Clinical Implications

A new mechanics-based diagnostic technology (quantitative percussion diagnostics) can provide information on the structural integrity of natural teeth after restoration. Higher normalized fit error (NFE) values correlate with more severe levels of remaining structural pathology and can predict future vulnerability for clinicians and patients. NFE values after restoration provide critical risk assessment data not available with conventional dental diagnostics. It can also help quantitatively assess structural integrity outcomes to improve treatment choices based on relevant mechanical evidence.

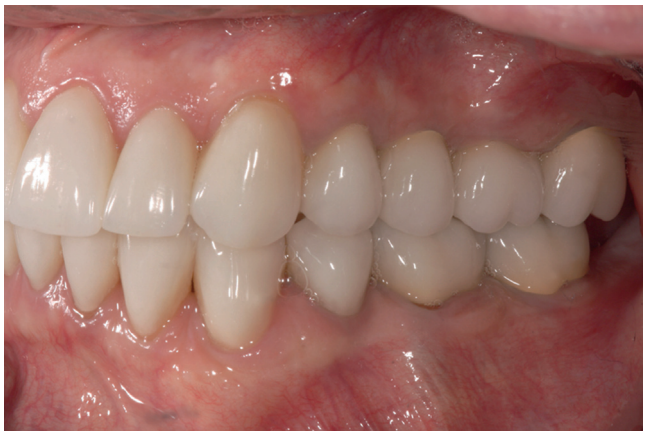

Figure 1. Lateral view of participant F after treatment showing definitive results of 3 years of interdisciplinary care.

longevity of their restored teeth and show the importance of preventive therapies such as nighttime occlusal device use. A quantitative metric would also help the clinician evaluate the structural impact of new and accepted dental treatments. Most diagnostic methods lack the ability to diagnose pathology hidden under radiopaque restorations or assess structural strength under loading conditions.

Quantitative percussion diagnostics (QPD) is a mechanics-based methodology that has been used clinically to analyze the structural integrity of teeth and dental implants by measuring the level of micromobility in the structure.[3-6] In these studies, 2 parameters were evaluated for each specimen using QPD: the loss coefficient (LC) and the normalized fit error (NFE). The LC characterizes the overall mobility of the site, and the NFE indicates the degree of local instabilities indicated by micromovement, which can arise from localized defects such as cracks, caries, loss of cement seal, or bone loss at the site. The explanation for determining the LC is given elsewhere.[4,5] 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 (ERG), can be useful for illustrating the overall and localized stability of a given site.[4-6] A description of how the NFE is determined during QPD is given in the appendices of several publications.[5-7]

A previous in vitro study showed QPD to be a highly predictable diagnostic aid for the identification of structural defects in teeth, even structural defects hidden under restorations or within the body of the tooth structure.[6] The predictive quality of QPD was shown in the before treatment assessment compared with the actual disassembly results recorded in video and written documentation. The mechanical diagnostic provided 100% sensitivity and 96% specificity.

A recently published in vivo study showed the effectiveness of QPD in identifying high-risk sites with structural pathologic micromovement. In this clinical trial on participants undergoing restorative treatment, the levels of NFE ratings were established for sites that possessed no, mild, moderate, or severe structural instability. Each site was disassembled under a microscope (Global Surgical) at ×8 to ×14 magnification using dye penetrant (Toluidine Blue O Indicator; Taylor) and a transillumination wand (TI2200; Kerr Corp) as described in a previous report.[7] 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 vitro analysis using finite element models can predict tooth strength but is not practical for clinical trials.[8] Because of the many variables that can influence the clinical performance and survival of restorations, no single test can currently predict clinical stability and success.[9]

The present study examined the ability of QPD to provide the clinician with information on the structural health of a tooth after restorative treatment. The results before the restoration were reported earlier and demonstrated consistency between NFE values and 4 levels of pathology (none, mild, moderate, and severe).[7] In particular, QPD exhibited at least 92% overall specificity (95% CI, 0.911-0.997) and 100% sensitivity (95% CI, 0.940-1.000). Also, for each standard deviation of increasing NFE, the tooth site was 12 times more likely to have more severe pathology than not, showing that the NFE values strongly discriminated among sites based on clinical pathology. QPD was found to be more effective in identifying structural pathology than radiographs, clinical

examination, or patient-reported symptoms.[7] The present work was focused on the ability of the NFE to indicate structural stability change after treatment. The research hypothesis was that QPD would also provide knowledge of the revised level of structural stability after restorative work.

MATERIAL AND METHODS

The same sample group of 8 human participants with a total of 60 sites that received restorative treatment in the initial part of this clinical study[7] were given a QPD complete-mouth evaluation after the restoration. The clinical data findings were then compared with the NFE data sets before the restoration, and paired *t* tests were performed for each site to determine whether a significant change in NFE had resulted from the restoration of the site.

The participants were selected for this IRB-approved study within a private prosthodontic practice from patients scheduled for restorative care, ranging from conservative bonded ceramic restorations to more extensive complete-coverage metal ceramic restorations with endodontic treatment. The inclusion/exclusion criteria were straightforward: the patients were diagnosed for restorative treatment and had no severe medical complications. The diagnosis for restorative care for the 60 sites was based on failing restorations, symptoms of a cracked tooth, wear, occlusal refinement, esthetics, or other issues not necessarily related to structural pathology. The restoration process provided the study with the opportunity to evaluate the correlation between structural pathology as indicated by any sources of micromovement observed and QPD results. The sites for this follow-on study were the same as those reported earlier for the initial study before the restoration.[7] The number of these sites for the initial study was based on the statistically significant sample size from an earlier in vitro study of cracks in extracted natural teeth.[6] Each participant signed informed consents, and IRB-approved protocols were followed.

The QPD was performed immediately before restorative work had begun and within 1 to 2 weeks after restorations had been delivered. A percussion probe diagnostic instrument (Periometer; Perimetrics LLC) that recorded and analyzed the percussion response of teeth was used. A single QPD test consists of data acquisition for 10 percussions on the tooth. Each site was tested 3 times, for a total of 30 sets of percussion data for each site. 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, the location and size of any fractures, and other structural weaknesses, were charted on a written dental assessment tool (DAT) as previously reported.[7] Each site was prepared for appropriate tooth preparations, impression, and interim restoration. Any tooth requiring follow-up procedures, such as endodontic treatment or extraction, was scheduled for treatment, and the outcome was 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. Approximately 2 weeks later, each participant received an after treatment QPD testing to evaluate changes in structural stability and to establish a new structural stability baseline for each restored site. The published initial data analysis focused on the NFEs before treatment and the relationship they had to the actual disassembly findings and was the first phase of this study.[7] The current study provided a comparison between the NFEs before and after treatment to evaluate the impact of the restorative dentistry on the structural stability of each site. NFE values for each site were determined from the 30 data sets acquired using QPD (N=30) as described for the first phase of the study.[7]

To analyze the change in NFE values after restoration, a linear model was fit for the regression of the mean within-site change in NFE value based on an indicator of the pathology rating. To account for clustering of sites within subject, a random effect was included in the model for the patient, although the intrapatient correlation was found to be small (estimated intrapatient correlation was 0.01). Robust standard errors were used to guard against model misspecification.[10] Next, a cumulative logistic regression model was used to model the probability of each pathology rating based on the NFE values in the before treatment phase of the study.[11] Here the pathology rating among sites was treated as independent, in that the intrapatient correlation was found to be negligible (estimated intrapatient correlation was 5.8×10^{-9}). The model was then used to predictively classify the rating after the restoration based on NFE values. The estimated NFE ratings after restoration were then compared with the ratings before treatment, and the diagnostic potential of the rating after restoration was explored as a marker for risk of pathology. All analyses were completed using the programming environment R (v3.2.3; R Foundation for Statistical Computing).[12]

RESULTS

Figure 2 shows the before treatment NFE results represented by orange bars and the after treatment NFE means represented by black circles, with an error bar indicating the standard deviation for each of the 60 sites tested. QPD testing after treatment for the entire set of 60 sites indicated an overall lowering of the average NFE

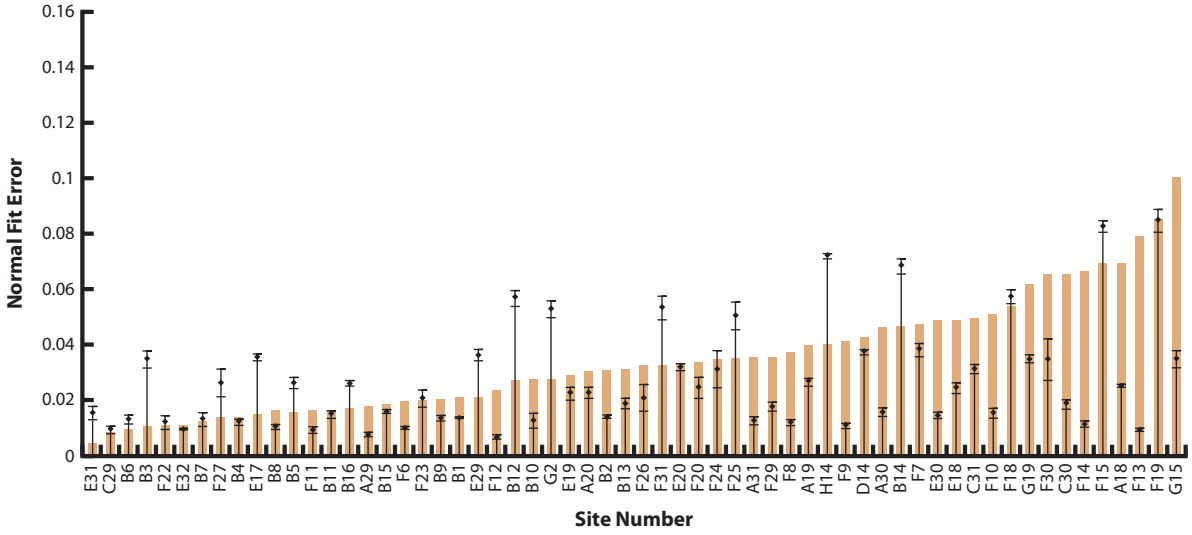

Figure 2. Normalized fit error (NFE) results after treatment for 60 sites in study showing generalized decrease in structural pathology as measured by drop in pathologic micromovement. Orange bars represent NFE values before treatment and drop lines represent NFE values after treatment with error bars. Average NFE reduction for 60 sites was from 0.035 to 0.027, representing a 33% increase in structural stability for group.

from 0.035 to 0.027. Fifty-one of the 60 sites (85%) fell below an NFE of 0.04, representing a greatly stabilized tooth site sample group. Only 9 sites remained in the higher NFE range of 0.04 to 0.09, and only 2 sites had an NFE over 0.08. Table 1 lists paired *t* test derived *P* values between the before and after treatment mean NFE values for each individual site (general sample *P*=.006).

An example of a site that improved is site C31, which presented with a Class I amalgam with slight marginal leakage.[7] The preexisting restoration was small, and no dentinal fractures were found with the clinical microscope, dye penetrant, or transillumination. However, the site had a high NFE, indicating severe internal pathologic micromovement.[7] After placement of a conservative Class I composite resin restoration, the NFE fell from 0.049 to 0.031 but remained at a level consistent with residual tooth fracture. Accordingly, this outcome either corresponded to a QPD false positive result or a significant defect still in the structure that was not observed visually during disassembly. A plot of QPD response in terms of energy return as a function of time[3-6] is shown in Figure 3A for 10 sets of data (1 test) for site C31 before restoration. A corresponding plot for site C31 after restoration is shown in Figure 3B. These graphs reveal the improvement in the percussion response for site C31 from before to after treatment, confirming the increase in structural stability after treatment but still showing unseen structural pathology. We note that a nearly symmetric single-peak response is associated with a defect-free site.[4-7]

Summaries of the distribution of the change in NFE values ($\times 10^2$) after restoration are shown in Table 2, where median and IQR (interquartile range) were tabulated by pathology rating. The median change in NFE value was about zero among sites with a clinical pathology rating of "None." Otherwise, the median (absolute) change was an increasing function of the pathology rating. The distribution of NFE changes was also graphed by pathology rating in Figure 4, where panel A shows mean within-site change in NFE values with plus-and-minus 1 standard deviation (SD) and panel B shows boxplots of the change in NFE values. Among sites with a clinical rating of None, the after restoration mean change was about zero. In contrast, after restoration mean NFE value declined among sites with clinical ratings of "Mild," "Moderate," and "Severe," where NFE values decreased for a majority of the sites (Fig. 4).

Estimated mean within-site change in NFE value is listed in Table 3. In overall ratings, the estimated mean within-site change in NFE values ($\times 10^2$) was -0.86 (mean change = -0.86, 95% CI, -1.68, -0.04). Among sites with Severe ratings, however, the estimated mean within-site change in NFE $\times 10^2$ values was -2.22 (mean change = -2.22, 95% CI -3.22, -1.22, *P*<.001). Mean change among sites with Severe ratings was significantly different from zero at a nominal α-level of .05.

A predictive model was developed earlier for the pathology rating based on NFE values from the before treatment phase of the study (Fig. 5).[7] This model was used in the present work to predictively classify the after restoration rating based on the NFE values after treatment. The estimated after restoration NFE ratings were compared with the before restoration ratings, and the diagnostic potential of the after restoration rating was explored as a marker for risk of pathology after restoration. The results of a comparison of after restoration NFE ratings are listed in Table 4, where rows represent the

Table 1. Before and after normalized fit error paired *t* test, *P* values, and clinical outcome for individual sites

Site Code	Normal Fit Error Before	NFE Standard Deviation Before	Normal Fit Error After	NFE Standard Deviation After	*P*	Change
A18	0.06909	0.00160	0.02512	0.00066	<.001	Improved
A19	0.03922	0.00371	0.02650	0.00118	<.001	Improved
A20	0.02997	0.00166	0.02227	0.00168	<.001	Improved
A29	0.01720	0.00094	0.00789	0.00083	<.001	Improved
A30	0.04599	0.00150	0.01557	0.00147	<.001	Improved
A31	0.03522	0.00132	0.01257	0.00147	<.001	Improved
B1	0.02077	0.00082	0.01374	0.00046	<.001	Improved
B2	0.03042	0.00102	0.01403	0.00050	<.001	Improved
B3	0.01033	0.00164	0.03473	0.00285	<.001	Worse
B4	0.01392	0.00145	0.01186	0.00109	.002	Improved
B5	0.01592	0.00242	0.02629	0.00205	<.001	Worse
B6	0.00903	0.00035	0.01288	0.00152	<.001	Worse
B7	0.01240	0.00119	0.01307	0.00232	.428	No Change
B8	0.01568	0.00176	0.01036	0.00074	<.001	Improved
B9	0.02042	0.00763	0.01349	0.00089	.011	Improved
B10	0.02719	0.00241	0.01240	0.00260	<.001	Improved
B11	0.01643	0.00091	0.01493	0.00118	.005	Improved
B12	0.02695	0.00333	0.05662	0.00276	<.001	Worse
B13	0.03065	0.00103	0.01876	0.00164	<.001	Improved
B14	0.04670	0.00158	0.06828	0.00280	<.001	Worse
B15	0.01812	0.00177	0.01606	0.00072	.003	Improved
B16	0.01691	0.00183	0.02625	0.00094	<.001	Worse
C29	0.00864	0.00062	0.00937	0.00121	.110	No Change
C30	0.06498	0.00358	0.01871	0.00161	<.001	Improved
C31	0.04958	0.00668	0.03130	0.00149	<.001	Improved
D14	0.04237	0.00092	0.03736	0.00062	<.001	Improved
E17	0.01497	0.00051	0.03537	0.00122	<.001	Worse
E18	0.04855	0.00151	0.02448	0.00175	<.001	Improved
E19	0.02897	0.00086	0.02238	0.00224	<.001	Improved
E20	0.03321	0.00126	0.03179	0.00124	.020	No Change
E29	0.02077	0.00146	0.03615	0.00199	<.001	Worse
E30	0.04835	0.00113	0.01447	0.00083	<.001	Improved
E31	0.00420	0.00026	0.01568	0.00248	<.001	Worse
E32	0.01124	0.00049	0.00962	0.00053	<.001	Improved
F6	0.01928	0.00153	0.01030	0.00069	<.001	Improved
F7	0.04725	0.00216	0.03810	0.00236	<.001	Improved
F8	0.03717	0.00148	0.01194	0.00127	<.001	Improved
F9	0.04091	0.00146	0.01089	0.00070	<.001	Improved
F10	0.05097	0.00196	0.01546	0.00175	<.001	Improved
F11	0.01632	0.00024	0.00911	0.00050	<.001	Worse
F12	0.02358	0.00734	0.00654	0.00071	<.001	Improved
F13	0.07897	0.00887	0.00924	0.00068	<.001	Improved
F14	0.06597	0.00379	0.01129	0.00086	<.001	Improved
F15	0.06894	0.00497	0.08255	0.00204	<.001	Worse
F18	0.05376	0.00475	0.05736	0.00258	.051	No Change
F19	0.08515	0.01291	0.08459	0.00416	.898	No Change
F20	0.03362	0.00123	0.02448	0.00375	<.001	Improved
F22	0.01051	0.00076	0.01219	0.00255	.060	No Change
F23	0.01941	0.00080	0.02067	0.00291	.203	No Change
F24	0.03452	0.00088	0.03118	0.00673	.139	No Change
F25	0.03490	0.00093	0.05036	0.00491	<.001	Worse
F26	0.03245	0.00094	0.02072	0.00466	<.001	Improved
F27	0.01383	0.00186	0.02591	0.00500	<.001	Worse
F29	0.03538	0.00085	0.01732	0.00179	<.001	Improved
F30	0.06491	0.00446	0.03461	0.00756	<.001	Improved
F31	0.03259	0.00153	0.05310	0.00421	<.001	Worse
G2	0.02758	0.00146	0.05270	0.00296	<.001	Worse
G15	0.09966	0.00326	0.03475	0.00312	<.001	Improved
G19	0.06161	0.00207	0.03475	0.00126	<.001	Improved
H14	0.04010	0.00160	0.07190	0.00090	<.001	Worse

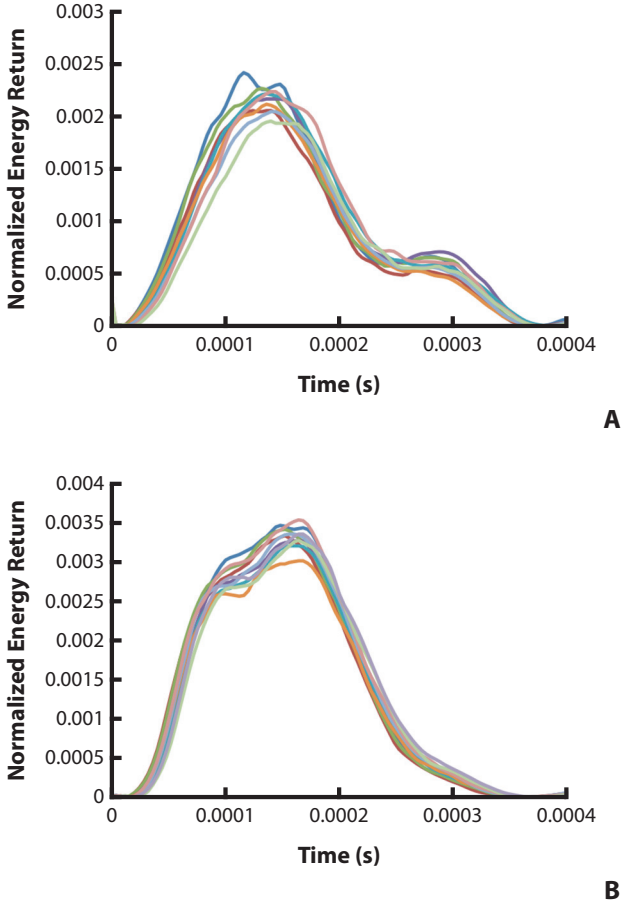

Figure 3. Percussion response measured for site C31. A, Before treatment. B, After treatment.

before restoration rating and columns represent the estimated pathology based on NFE values after restoration. There were a total of 16 sites, for example, with a before restoration rating of Severe. Of these, based on

Table 2. Summaries of normalized fit error values before and after restoration

NFE $\times 10^2$	Before Restoration (n=60)	After Restoration (n=60)	Change (n=60)
Overall	3.16 (1.71-4.70)	2.07 (1.27-3.47)	-0.68 (-1.82-0.37)
Pathology			
None (20)	1.53 (1.09-1.71)	1.40 (1.03-2.61)	0.07 (-0.37-0.99)
Mild (11)	2.72 (2.22-2.95)	1.37 (1.22-2.93)	-0.70 (-1.59-0.44)
Moderate (13)	3.45 (3.26-3.54)	2.45 (1.73-3.18)	-1.17 (-1.64 to -0.33)
Severe (16)	6.33 (4.75-6.90)	3.47 (1.71-6.28)	-2.86 (-4.51-0.15)

Overall summaries and summaries by clinical rating before restoration. Reporting median and interquartile range (IQR). Unit is patient-site.

after restoration NFE values, there were 5 sites classified as None, 2 as Mild, 4 as Moderate, and 5 as Severe. As listed in the last row of Table 4, these sites respectively represented about 31%, 12%, 25%, and 31% of the severely rated sites. One may speculate that the 5 sites with an after restoration estimate of Severe may be at some appreciable risk of failure or other complication. A total of 40 sites were recorded with a clinical rating of Mild, Moderate, or Severe (Table 5). Of these, 24 sites had after restoration predictive classifications of Mild, Moderate, or Severe. The proportion of sites at some after restoration risk was then estimated to be 60% (95% CI 43.9-74.3). The confidence interval excludes 0%, so these results were strongly consistent with the notion that restored sites will often require some level of rigorous follow-up care after the restoration. In addition, 7 of the 20 sites initially classified in the None category were found to have NFE values in the Mild or Moderate categories, suggesting a need to test all sites after the restoration, regardless of initial assessment.

On the positive side, again from Table 5, of those sites with clinical ratings of Mild, Moderate, or Severe before the restoration, 54.5%, 38.5%, and 31.2%, respectively, had predictive classifications of None after the restoration. These sites may provisionally be viewed as at low risk for complications after the restoration, perhaps requiring a less rigorous follow-up program.

An alternative strategy to classification after the restoration may be based on the distribution of the NFE values before restoration among sites with a clinical pathology rating of None. These sites may be viewed as a normative sample of nonpathologic NFE values against which to flag NFE values after restoration as "outlying" or "far outlying." These categories may provisionally be viewed as indicating 2 levels of risk of pathology after restoration. Using the 5-number summary of the proposed normative sample, outlying values were defined as after restoration NFE values greater than the third quartile plus 1 interquartile range (IQR), while far outlying values were defined as after restoration NFE values greater than the third quartile plus 2 IQRs.[13] (see Table 1 for relevant numerical summaries). Here

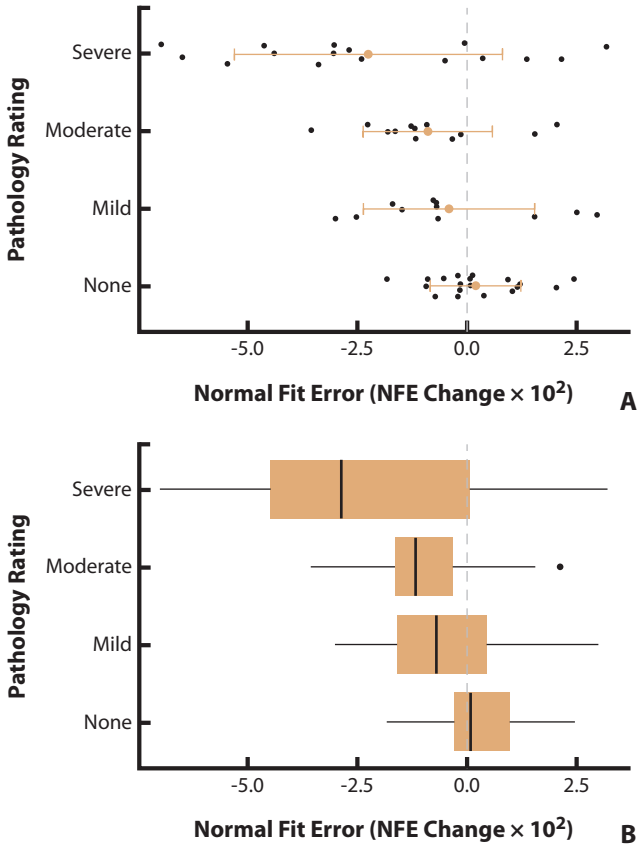

Figure 4. Distribution of change in normalized fit error (NFE) values by pathology rating. Unit is patient-site. A) Spread of within-site change in NFE values by pathology rating. Error bars show mean change in NFE value plus-and-minus one standard deviation. Mean change was about zero among sites with clinical rating of None. After restoration, mean NFE value declined among sites with clinical ratings of Mild, Moderate, and Severe. B) Boxplots of change in NFE values by pathology rating. Boxes bound range of middle 50% of each sample. Median change in rating-group None was about zero. NFE values after restoration were reduced for majority of sites with clinical rating of Mild, Moderate, or Severe. Greater variability was observed in severe rating. Outlier was noted at rating moderate.

the inner cutoff was 2.63 $\times 10^{-2}$ NFE, and the outer cutoff was 3.56 $\times 10^{-2}$ NFE. These alternative NFE-cutoffs were then used to classify the after restoration NFE values, flagged here as outlying or far outlying, for comparison with the before restoration ratings. The results are listed in Table 5, where rows represent the before restoration rating and columns the outlier status based on after restoration NFE values. For example, a total of 16 sites had a before restoration rating of Severe. Of these, based on after restoration NFE values, 7, 3, and 6 sites were classified as "None," "Outside," and "Far Outside," respectively. As listed in the last row of Table 5, these sites represented about 44%, 19%, and 38% respectively of the severely rated sites. One may again speculate that the 6 sites with an after restoration status of far outlying

Table 3. Mean within-site change in normalized fit error values after restoration, overall and by clinical pathology rating

Normalized Fit Error after Restoration	Mean Change × 10^2 (95% CI)	*P*	n
Overall	-0.86 (-1.68, -0.04)	.039	60
Rating before restoration			
None	0.18 (-0.74, 1.09)	.71	60
Mild	-0.43 (-1.63, 0.78)	.49	60
Moderate	-0.85 (-1.98, 0.29)	.14	60
Severe	-2.22 (-3.22, -1.22)	<.001	60

Significant improvement (reduction in normalized fit error value) was registered for sites initially at moderate or severe pathology level. (α=.05).

Table 4. Distribution of sites by clinical pathology: Model-based normalized fit error classifier

	After Restoration NFE Pathology				
Before Restoration	None	Mild	Moderate	Severe	Total
Counts					
None	13	4	3	0	20
Mild	6	2	1	2	11
Moderate	5	3	3	2	13
Severe	5	2	4	5	16
Fractions					
None	0.65	0.2	0.15	0	1
Mild	0.55	0.18	0.09	0.18	1
Moderate	0.38	0.23	0.23	0.15	1
Severe	0.31	0.12	0.25	0.31	1

Pathology before restoration was cross tabulated with pathology after restoration using empirical cutoffs for normalized fit error (NFE) classifier based on after restoration NFE values. Rows represent before restoration classification. Columns represent after restoration (predictive) classification.

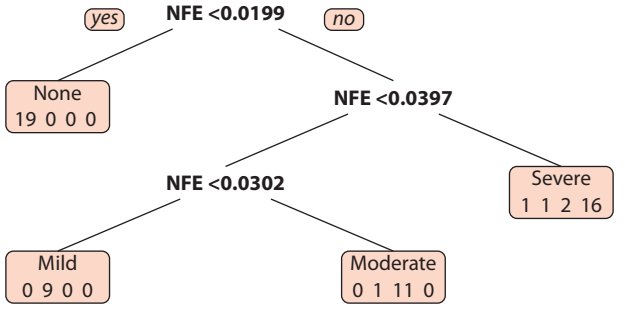

Figure 5. Classification tree based on normalized fit error values before restoration.[7] Optimal cutoffs between pathology classifications were determined by minimizing probability of misclassification across tree.

Table 5. Distribution of sites by clinical pathology: Normative-sample classifier

	After Restoration NFE Classifier			
Before Restoration	None	Outlying	Far Outlying	Total
Counts				
None	17	3	0	20
Mild	8	0	3	11
Moderate	7	3	3	13
Severe	7	3	6	16
Fractions				
None	0.85	0.15	0	1
Mild	0.73	0	0.27	1
Moderate	0.54	0.23	0.23	1
Severe	0.44	0.19	0.38	1

Pathology before restoration was cross tabulated with classification after restoration in normative sample of nonpathologic sites. After restoration values were classified as outliers or far outliers relative to extremes of distribution of before restoration normalized fit error (NFE) values among sites with ratings of None before restoration. Rows represent classification before restoration. Columns represent classification after restoration.

may be at some appreciable risk of failure or other complication after restoration.

Of the total of 40 sites with a clinical rating of Mild, Moderate, or Severe (Table 5), 18 sites had after restoration classifications of outlying or far outlying. The proportion of sites at some after restoration risk was then estimated to be 45% (95% CI 30-60.9), an estimate that again excluded 0%. On the positive side, again from Table 5, of those sites with before restoration clinical ratings of Mild, Moderate, or Severe, 72.7%, 53.8%, and 43.8%, respectively, had after restoration classifications of None.

DISCUSSION

Either of these 2 approaches to classification after the restoration may be developed further for clinical use. The model-based NFE classifier was tailored to discriminate maximally among clinical ratings based on before restoration NFE values, and the after restoration classification has the virtue of calling upon an established set of clinical ratings. Although a principled approach, the cutoffs ultimately depend on the quality of the model. The alternative NFE classifier required only a normative sample of NFE values from a representative sample of nonpathologic sites. The cutoffs for outlying and far outlying were introduced here to serve an ad hoc purpose, but they were robust against any misspecification of the predictive model. We note, however, that the cutoffs from the model-based classifier were 1.99, 3.02, and 3.97 $\times 10^{-2}$ NFE as indicated in Figure 5.[7] It turned out that the cutoffs based on the normative sample of nonpathologic sites, namely 2.63 and 3.56, were approximately equal to the midpoints between the first and second and the second and third model-based cutoffs, respectively. The 2 proposed methods will thus yield qualitatively very similar prospective alerts about after restoration risk, although either method will need to be developed further with larger sample sizes.

The statistical results show that mechanical testing provides more definitive information regarding the structural health of a patient's teeth than other more traditional methods. A more detailed examination of the history for restored sites that tested structurally damaged can provide additional information on the interpretation of the mechanical testing results and and we intend to address this in a subsequent paper.

The QPD readings after restoration for all 60 sites created a new baseline reading for each participant for

future monitoring. Years of service can be reasonably expected if patients are compliant with protective occlusal devices, eliminate noxious habits such as ice chewing, and have consistent periodic QPD monitoring to alert the clinician of any further breakdown. None of the 9 after treatment high-risk sites have required further treatment after more than 5 years of monitoring and protection.

CONCLUSIONS

Based on the present study data, the following conclusions were made:

1. QPD was able to provide the clinician with a revised level of structural stability after restorative treatment that could identify high-risk sites requiring further monitoring.
2. QPD metrics after restoration provide a new risk assessment tool, a patient educational tool, and a motivator for preventive compliance.
3. Further research is indicated to test the limits of information provided by this new diagnostic paradigm in follow-up assessments after restorative treatment.

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