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CLINICAL RESEARCH

Ten-year retrospective study of the effectiveness of quantitative percussion diagnostics as an indicator of the level of structural pathology in teeth

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ABSTRACT

Statement of problem. Conventional dental diagnostic aids are only partially effective in diagnosing structural defects such as cracks in teeth. A more predictable diagnostic for structural instability in the mouth is needed.

Purpose. The purpose of this clinical study with an increased population size was to evaluate the effectiveness of diagnosing structural instability by using the quantitative percussion diagnostics (QPD) system and to evaluate the influence of independent variables on the relationship between normal fit error (NFE) and observed structural instability found during the clinical disassembly of teeth.

Material and methods. Twenty-two participants with 264 sites needing restoration were enrolled in an institutional review board–approved 10-year retrospective clinical study. Each site had been tested with the QPD system before being disassembled microscopically with video documentation, and the clinical disassembly results were recorded on a defect-assessment sheet. The NFE data were separately recorded from the preexisting records. The classification of structural pathology based on the disassembly observations for each of the 264 sites was conducted by the clinical researcher (C.G.S.) who was blinded to the NFE values.

Results. The 264 sites from 22 patients were classified as 8 in the none group, 87 in the moderate group, and 169 in the severe group based on the disassembly findings. The NFE data for the sites were analyzed by using the predefined NFE cutoffs that were independently generated from the previous cumulative logistic regression and decision tree model. For the cumulative logistic regression, 235 out of 264 sites were correctly classified with an agreement of 0.89 (adjusted 95% CI: 0.83-0.95). The number of correctly classified sites for the decision tree model was 234, and the agreement was also 0.89 (adjusted 95% CI: 0.83-0.94). For both cumulative logistic regression and decision tree models, the overall misclassification rate was less than 20% for any restoration material or restoration type. Therefore, the overall performance of NFE classification was consistently good, regardless of restoration material or type. In addition, the sensitivity of the severe category was above 90% for any restoration material or type for the decision tree model.

Conclusions. The QPD system was found to be a reliable diagnostic aid for classifying structural damage in the categories of none, moderate, or severe based on clinical disassembly findings under the clinical microscope and NFE values. Furthermore, it was determined that restoration type and restoration design were not significant factors in correlating structural pathology with NFE. (J Prosthet Dent 2019;■:■-■)

Conventional dental diagnostic aids based on imagery and patient symptoms are only partially effective for the detection of fine structural defects such as cracks in teeth or failing implants.[1-4] These defects can manifest additional instability during function in unrestored or restored teeth and implants. In the natural dentition, breakdown

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Clinical Implications

Quantitative percussion diagnostics, a diagnostic mechanical assessment of tooth and implant stability, provides a new diagnostic tool for the clinician which does not depend on visual assessment. QPD allows a clinician to assess the structural health of a patient's dentition in a manner consistent with loading received from mastication and parafunction. Clinical advantages include early indications of unrecognized structural breakdown, identification of sources of elusive pain due to fine-gap defects such as cracks in teeth, and the ability to recognize the need for preventive procedures while they can still be effective. Advanced knowledge of structural damage before restoration or the appearance of symptoms aids in treatment planning and the adoption of early preventive protocols.

beneath radiopaque restorations, cracks that are within the dentin, defects beneath the bone or soft tissues, or other common conditions related to structural integrity cannot be visually detected.[1,5]

Visual inspection, subjective patient symptoms, transillumination, dye penetration, and magnification are the most common techniques used to identify fine-gap structural pathologies such as cracks in teeth and loss of the cement seal in fixed restorations.[1-14] Additional techniques such as qualitative percussion, occlusal testing, and thermal pulp testing are only effective when the pulpal tissues are affected.[4,15,16]

An institutional review board–approved study was conducted to assess the clinical use of the quantitative percussion diagnostics (QPD) system, a new diagnostic methodology for the evaluation of structural pathology in teeth and implants.[17-19] The results of this study showed that the QPD system agreed with clinical disassembly findings in 55 of 60 comparisons (92% agreement). Moreover, the method achieved 98% specificity and 100% sensitivity for detecting structural pathologies observed during clinical disassembly. A parameter that gauges unstable micromovement, the normal fit error (NFE), was found to be highly predictive of advanced structural pathology. The conclusions from the data showed that the QPD system can provide the clinician with advance knowledge of the structural instability of teeth before restorative treatment begins. These studies showed that a mechanics-based diagnostic technology was able to provide important information on the structural integrity of teeth, just as earlier studies indicated that the QPD system was able to provide information on the structural integrity of dental implants.[2,20-27] However, the sample size of the clinical tooth study and the number of participants were limited, with only 60 sites from 8 different participants. Also, questions remained about potential influencers in the relationship between normal fit error (NFE) value and the structural pathology (none, mildmoderate, severe) observed during disassembly.

This article describes a retrospective study with 2 objectives designed to further evaluate these previous findings. Specifically, the first objective was to increase the population size to further analyze the effectiveness of the QPD system for assessing sites as either having none, moderate, or severe structural pathology. The second objective was to conduct a statistical analysis of the independent variables on the relationship between NFE and observed structural pathology (restoration material, restoration type, and patient characteristics). The research hypothesis was that the QPD system for assessing structural stability is consistent with clinical disassembly findings by using a clinical microscope with the aid of dye penetrant or transillumination and that restoration material or type does not influence the results significantly.

MATERIAL AND METHODS

A nonrandomized, single-center, retrospective institutional review board–approved study was designed to evaluate the ability of the QPD system to confirm none, moderate, and severe structural pathology of the periodontium and its associated fixed structures (teeth or implants) in a larger cohort of patients than previously tested. The 10-year retrospective study was performed on a total of 264 sites from 22 different participants in a private prosthodontic practice.

Records from the prosthodontic practice were screened by a research assistant to locate patients who had had pretreatment QPD testing before restorative treatment. The patients were then further screened to identify those with written clinical disassembly notes and video documentation obtained during the restorative care. The inclusion and exclusion conditions were the same as in the original study.[17]

Each of the identified sites received a QPD classification of structural pathology by using the NFE values from the percussion instrument (Periometer; Perimetrics LLC) and preestablished thresholds from the earlier studies. These values were compared with the principal investigators' structural pathology classifications based on clinical evaluation from the participant's written and video dental records made at the disassembly of each tooth. Also, the presence or absence of preexisting restorations was noted. All disassembly procedures

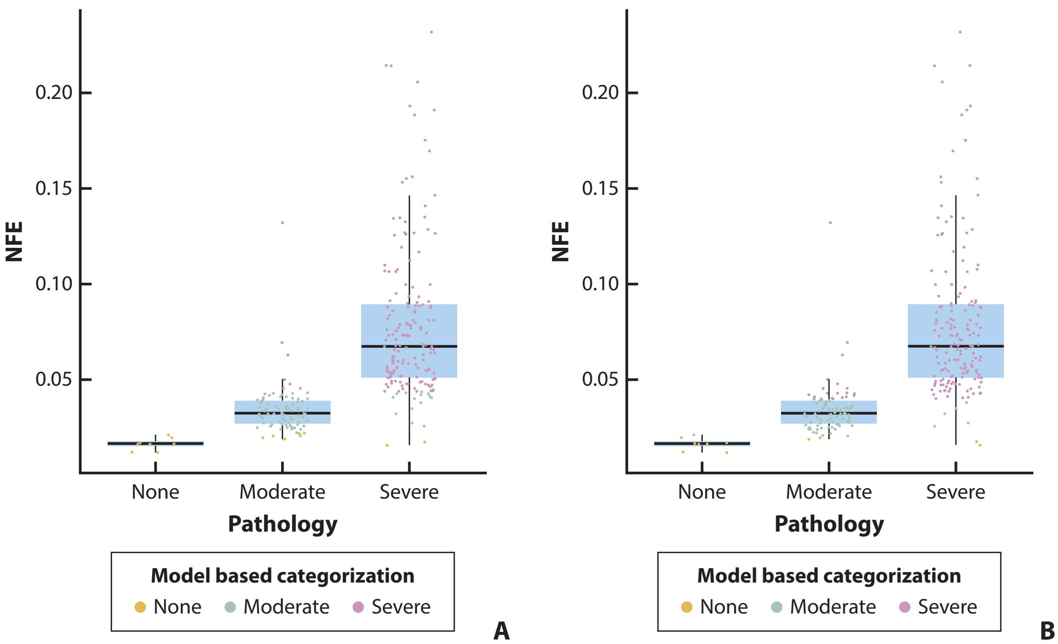

Figure 1. NFE value among different pathology groups colored by model-based categorization. A, Cumulative logistic regression model. B, Decision tree model. NFE, normal fit error.

were documented in written and video formats with the aid of a clinical surgical microscope (Global Surgical microscopes). The protocols for disassembly and analysis of the sites were consistent with those of the original clinical study.[17]

The percussion instrument digitized an analog signal from a hand-held percussion probe when tapped on a site (tooth or implant). Its software analyzed this signal and output a value of NFE and stored this value along with the raw signal data for each site tested.[18,19]

The classification of structural pathology on the 264 sites was conducted by a clinical researcher (C.G.S.), who was blinded to the NFE values. Charts and video recordings of disassembly of the sites during treatment were reviewed by the clinical researcher. The clinical researcher used current treatment guidelines to diagnose the disassembled sites into one of the 3 structural pathology classes before restoring the sites. An intraclass correlation coefficient was calculated, and the random effect in the ordinal regression model was included to account for the possible within-cluster correlation.

In previous studies, 2 separate statistical models, a cumulative logistic regression and a decision tree model, were fitted to quantify the predictive capability of NFE as a prognostic clinical tool. A set of NFE classification cutoffs were determined based on each of the 2 models. For the cumulative logistic regression model, NFE$\times 10^{-2}$ values of less than 2.23 were categorized as none, values between 2.23 and 4.40 were moderate, and values greater than 4.40 were severe. For the decision tree model, the NFE ($\times 10^{-2}$) cutoffs were 1.99 and 3.97, accordingly. In this present study, 2 sets of classification cutoffs on this 264-site retrospective data were examined and validated. Sensitivity and specificity were provided with 95% confidence interval for each classification rule. The correlation among different sites within a same participant could lead to biased confidence limits in the traditional confidence interval calculation for Bernoulli distribution. To correct for the underestimated (or overestimated) variance problem, a ratio estimator for the variance of clustered binary data was derived and applied to adjust the 95% confidence interval.[28,29] Furthermore, the classification performance on each restoration material or type group was also examined. Similarly, a percent of agreement, sensitivity, and specificity were provided with 95% confidence interval. Analyses were performed by using a statistical software program (R v3.3.3; The R Foundation).

RESULTS

The 264 sites were classified as none, moderate, or severe based on disassembly under the clinical microscope and predetermined criteria for the 3 clinical categories. The 264 sites from 22 participants were classified as 8 in the none group, 87 in the moderate group, and 169 in the severe group. The NFE data for the sites were analyzed by using the predefined NFE cutoffs that were independently generated from the previous cumulative logistic regression and decision tree model (Fig. 1). The mean ±standard deviation of NFE ($\times 10^{-2}$) for each diagnosis category was 1.65 ±0.32, 3.47 ±1.37, and 7.87 ±4.02.

Table 1. Percentage of agreement, sensitivity, and specificity with 95% confidence interval

Cumulative Logistic Regression			Decision Tree		
	Percentage of Agreement			Percentage of Agreement	
All	0.89 (0.83-0.95)		All	0.89 (0.83-0.94)	
	Sensitivity	Specificity		Sensitivity	Specificity
None	1.00 (1.00-1.00)	0.97 (0.94-1.00)	None	0.88 (0.61-1.00)	0.98 (0.97-1.00)
Moderate	0.85 (0.75-0.95)	0.92 (0.88-0.97)	Moderate	0.75 (0.63-0.87)	0.97 (0.94-0.99)
Severe	0.91 (0.85-0.96)	0.93 (0.87-0.99)	Severe	0.96 (0.93-0.99)	0.79 (0.67-0.91)

Table 2. Frequency distribution of clinical pathology ratings by tooth restoration material

	Pathology			
Material	**None (%)**	**Moderate (%)**	**Severe (%)**	**Total**
Amalgam	0 (0.00)	2 (10.00)	18 (90.00)	20
Composite or acrylic resin	2 (6.06)	10 (30.30)	21 (72.73)	33
Metal-ceramic/ceramic/gold	2 (1.68)	23 (19.33)	94 (78.99)	119
Unrestored	4 (4.35)	52 (56.52)	1. (39.13)	92

Table 3. Frequency distribution of clinical pathology ratings by tooth restoration type

	Pathology			
Restoration	**None (%)**	**Moderate (%)**	**Severe (%)**	**Total**
Crown/endodontic treatment and crown	2 (2.17)	12 (13.04)	78 (84.78)	92
Filling	1 (2.27)	10 (22.73)	33 (75.00)	44
Inlay/onlay/veneer	1 (2.78)	13 (36.11)	22 (61.11)	36
Unrestored	4 (4.35)	52 (56.52)	36 (39.13)	92

Table 1 shows the classification performance of the 2 sets of the model-based cutoffs side by side with the overall percentage of agreement and the sensitivity and specificity for each pathology category. For the cumulative logistic regression, 235 of 264 sites were correctly classified with a percentage of agreement of 0.89 (adjusted 95% CI: 0.83-0.95). The number of correctly classified sites in the decision tree model was 234, and the percentage of agreement was also 0.89 (adjusted 95% CI: 0.83-0.94). The overall performance was quite similar between the 2 models. However, it was noted that the specificity of the none and moderate categories was slightly higher in the decision tree model than in the regression model. Furthermore, the sensitivity of the severe category was also found to be 5% higher in the decision tree model. These results indicate that the decision tree classification rule performed better in terms of ruling out the severe situation when disassembly does not indicate severe pathology. Furthermore, the decision tree model gave a somewhat more conservative classification of NFE values for indicating severe pathology.

The NFE diagnostic ability was further tested on each restoration material and type. The frequency of clinical pathology ratings and the distribution of NFE by restoration material or type are shown in Tables 2 and 3 and Figure 2. Tables 4 and 5 show the overall percentage agreement and the sensitivity and specificity by restoration material and type with adjusted 95% confidence intervals. For both the cumulative logistic regression and decision tree model, the overall misclassification rates were all less than 20% for any restoration material or restoration type. Therefore, the overall performance of NFE classification was found to be consistently good, regardless of restoration material or type. The sensitivity of the severe category was always above 90% for any restoration material or type in the decision tree model.

DISCUSSION

The data supported the research hypothesis that the QPD system for assessing structural stability is consistent with clinical disassembly findings by using a clinical microscope with the aid of dye penetrant or transillumination and that restoration material or type do not influence the results significantly. The NFE parameter is based on the percussion response plotted as mechanical energy measured in the percussion rod versus time. NFE indicates the extent to which this response is different in shape from a uniform single peak that would be registered for a defect-free site. A common cause of this shape difference is rapid closing of a fine gap between 2 crack surfaces that produces unstable micromovement when the 2 surfaces contact each other during the percussion of the site. Figure 3 shows representative data for (1) a defect-free tooth and (2) a tooth containing a vertical crack. The crack gives rise to additional peaks in the energy-return response as indicated in Figure 3B. In the original 60-site study[17] and in the present work with 264 disassembled sites, the results indicated that the NFE value increases with advancing structural damage that causes the measured mechanical instability (additional peaks).

Combinations of unstable micromovements can be exhibited by the same site. The disassembly of numerous sites has revealed that mechanical instability can be generated from multiple sources of damage. Examples of multiple superimposed defects could be found in a site possessing a dentinal crack under a crown that has developed a loss of cement seal which led to microleakage. This example, even though not showing visible

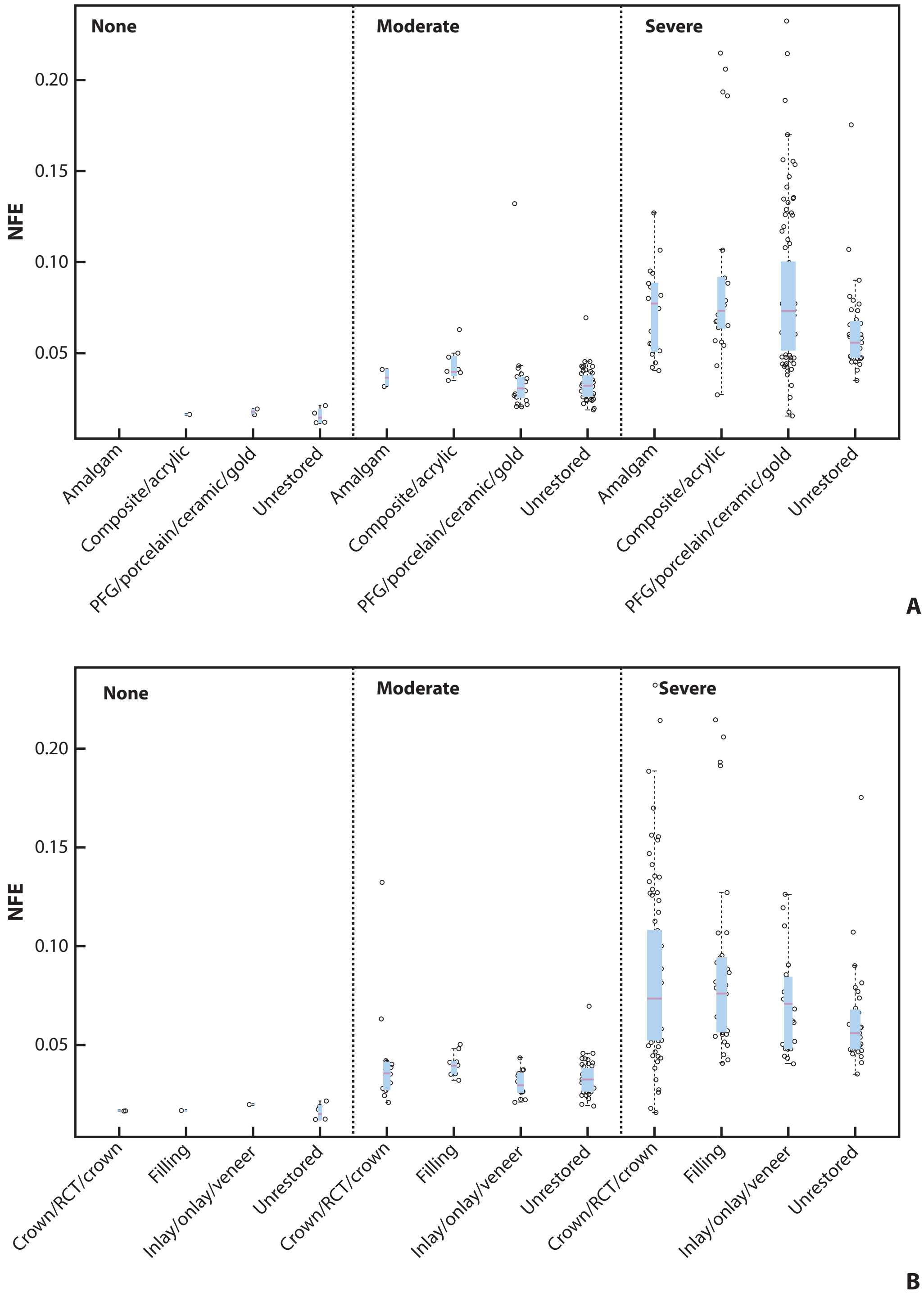

Figure 2. Distribution of NFE by pathology rating. A, By restoration material. B, By restoration type. Box plots are shown on top of scatter plots of NFE. NFE, normal fit error.

signs of breakdown, would show increasing NFE scores as the damage increases with time. In the original study of 60 sites in 8 patients and the present study of 264 sites in 22 patients, the normal fit error (NFE) strongly correlated with structural damage in a site, regardless of whether the detected instability was from a single source or multiple sources. This correlation between NFE and the structural pathology level observed under the microscope was also found to be independent of restoration type and preparation design. A limitation of this study is that the clinician during disassembly is limited to the view allowed by the depth of the preparation, which

Table 4. Mean and SD of NFE (×10^2) by pathology ratings and restoration material

Material	Cumulative Logistic Regression			Decision Tree		
Amalgam		Percentage of Agreement			Percentage of Agreement	
	All	0.90 (0.74-1.00)		All	0.95 (0.88-1.00)	
		Sensitivity	Specificity		Sensitivity	Specificity
	None	–	1.00 (1.00-1.00)	None	–	1.00 (1.00-1.00)
	Moderate	1.00 (1.00-1.00)	0.89 (0.72-1.00)	Moderate	0.50 (0.00-1.00)	1.00 (1.00-1.00)
	Severe	0.89 (0.72-1.00)	1.00 (1.00-1.00)	Severe	1.00 (1.00-1.00)	0.50 (0.00-1.00)
Composite or acrylic resin		Percentage of Agreement			Percentage of Agreement	
	All	0.85 (0.72-0.98)		All	0.82 (0.70-0.94)	
		Sensitivity	Specificity		Sensitivity	Specificity
	None	1.00 (1.00-1.00)	1.00 (1.00-1.00)	None	1.00 (1.00-1.00)	1.00 (1.00-1.00)
	Moderate	0.70 (0.36-1.00)	0.91 (0.82-1.00)	Moderate	0.50 (0.15-0.85)	0.96 (0.86-1.00)
	Severe	0.90 (0.80-1.00)	0.75 (0.46-1.00)	Severe	0.95 (0.85-1.00)	0.58 (0.31-0.86)
Metal-ceramic/ceramic/gold		Percentage of Agreement			Percentage of Agreement	
	All	0.88 (0.79-0.97)		All	0.93 (0.88-0.99)	
		Sensitivity	Specificity		Sensitivity	Specificity
	None	1.00 (1.00-1.00)	0.95 (0.90-1.00)	None	1.00 (1.00-1.00)	0.98 (0.95-1.00)
	Moderate	0.78 (0.62-0.95)	0.93 (0.87-0.99)	Moderate	0.87 (0.76-0.98)	0.97 (0.93-1.00)
	Severe	0.90 (0.83-0.98)	0.96 (0.92-1.00)	Severe	0.95 (0.89-1.00)	0.88 (0.77-0.99)
Unrestored		Percentage of Agreement			Percentage of Agreement	
	All	0.91 (0.85-0.97)		All	0.84 (0.72-0.95)	
		Sensitivity	Specificity		Sensitivity	Specificity
	None	1.00 (1.00-1.00)	0.98 (0.95-1.00)	None	0.75 (0.02-1.00)	0.98 (0.95-1.00)
	Moderate	0.90 (0.82-0.99)	0.93 (0.84-1.00)	Moderate	0.75 (0.59-0.91)	0.95 (0.89-1.00)
	Severe	0.92 (0.82-1.00)	0.95 (0.87-1.00)	Severe	0.97 (0.93-1.00)	1 (0.63-0.98)

Table 5. Mean and SD of NFE (×10^2) by pathology ratings and restoration type

Type	Cumulative Logistic Regression			Decision Tree		
Crown/endodontic treatment and crown		Percentage of Agreement			Percentage of Agreement	
	All	0.87 (0.77-0.96)		All	0.89 (0.81-0.97)	
		Sensitivity	Specificity		Sensitivity	Specificity
	None	1.00 (1.00-1.00)	0.97 (0.91-1.00)	None	1.00 (1.00-1.00)	0.98 (0.93-1.00)
	Moderate	0.75 (0.49-1.00)	0.91 (0.84-0.98)	Moderate	0.67 (0.40-0.93)	0.95 (0.90-1.00)
	Severe	0.88 (0.79-0.97)	0.86 (0.68-1.00)	Severe	0.92 (0.85-1.00)	0.71 (0.47-0.96)
Filling		Percentage of Agreement			Percentage of Agreement	
	All	0.91 (0.81-1.00)		All	0.91 (0.84-0.97)	
		Sensitivity	Specificity		Sensitivity	Specificity
	None	1.00 (–)	1.00 (1.00-1.00)	None	1.00 (–)	1.00 (1.00-1.00)
	Moderate	0.80 (0.50-1.00)	0.94 (0.87-1.00)	Moderate	0.60 (0.39-0.81)	1.00 (1.00-1.00)
	Severe	0.94 (0.87-1.00)	0.82 (0.56-1.00)	Severe	1.00 (1.00-1.00)	0.64 (0.44-0.83)
Inlay/onlay/veneer		Percentage of Agreement			Percentage of Agreement	
	All	0.86 (0.70-1.00)		All	0.97 (0.90-1.00)	
		Sensitivity	Specificity		Sensitivity	Specificity
	None	1.00 (–)	0.91 (0.81-1.00)	None	1.00 (–)	1.00 (1.00-1.00)
	Moderate	0.77 (0.66-0.87)	0.91 (0.77-1.00)	Moderate	0.92 (0.69-1.00)	1.00 (1.00-1.00)
	Severe	0.91 (0.75-1.00)	1.00 (1.00-1.00)	Severe	1.00 (1.00-1.00)	0.93 (0.71-1.00)
Unrestored		Percentage of Agreement			Percentage of Agreement	
	All	0.91 (0.85-0.97)		All	0.84 (0.72-0.95)	
		Sensitivity	Specificity		Sensitivity	Specificity
	None	1.00 (1.00-1.00)	0.98 (0.95-1.00)	None	0.75 (0.02-1.00)	0.98 (0.95-1.00)
	Moderate	0.90 (0.82-0.99)	0.93 (0.84-1.00)	Moderate	0.75 (0.59-0.91)	0.95 (0.89-1.00)
	Severe	0.92 (0.82-1.00)	0.95 (0.87-1.00)	Severe	0.97 (0.93-1.00)	0.80 (0.63-0.98)

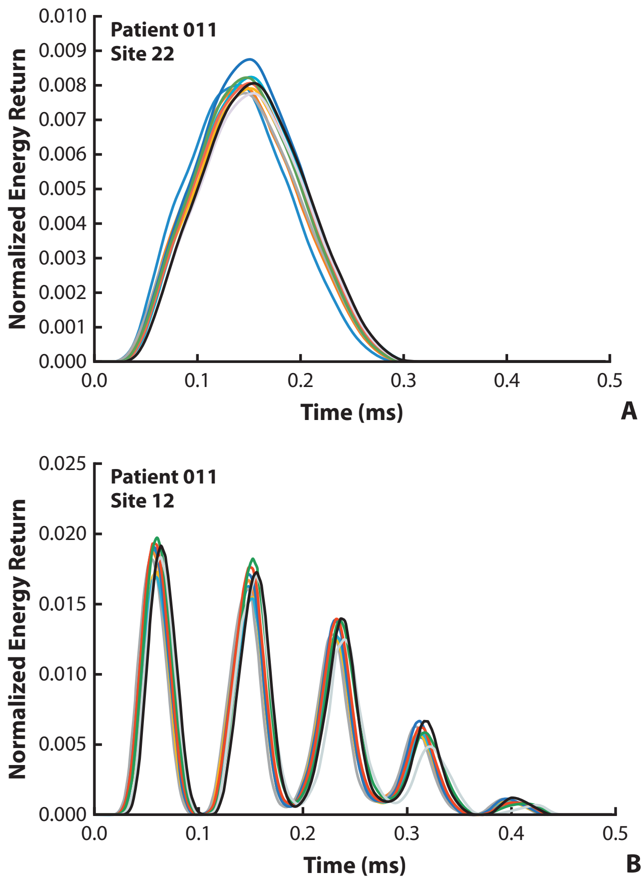

Figure 3. QPD data from 10 percussion response curves. A, Defect-free tooth. B, Tooth with vertical crack. QPD, quantitative percussion diagnostics.

often terminated superior to the bone and gingival tissues. Also, in conservative minimally invasive preparation designs, the preparations often terminate in enamel and do not allow detection of dentinal cracks. Therefore, the clinician may not be able to observe structural defects that are not in their visual field. As an additional means of verification, ongoing and future studies will use finite element analysis to verify results from QPD that indicate structural pathology.

CONCLUSIONS

Based on the findings of this expanded clinical study of 264 sites in 22 participants, the following conclusions were drawn:

1. The effectiveness of the QPD system and NFE used as metrics in percussion diagnostics was confirmed.
2. The concept of unstable micromovement that results from a fine-gap defect in a tested site was demonstrated as being an accurate indicator of structural pathology.
3. The independent variables of restoration material and restoration type were found to not significantly affect the testing results.
4. The sensitivity of severe pathology classification was all above 90% for any restoration material or type in the decision tree model.

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