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AI-based predictions of nickel-titanium file separation using thermal imaging: An *in vitro* study

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Abstract:
Nickel-titanium rotary file separation is a sudden procedural complication and clinicians currently lack a non-destructive warning system that can identify fatigue-related failure before fracture occurs. Therefore, it is of interest to evaluate the whether thermal imaging combined with machine learning could predict imminent file separation during simulated curved-canal instrumentation. A total of 120 rotary files were tested in standardized stainless-steel curved canals and thermal signals, time to fracture, rotational cycles and file surface changes were recorded for artificial intelligence model training and validation. Files that separated showed a significantly higher terminal temperature rise than non-separated controls (6.8 ± 1.7°C vs 2.4 ± 0.9°C; $p<0.001$) and the gradient boosting model predicted separation with 91.7% accuracy, 0.93 sensitivity, 0.90 specificity and an AUC of 0.96. Thus, thermal imaging-based artificial intelligence showed high predictive performance for impending nickel-titanium file separation and may support safer preclinical assessment of rotary endodontic instruments.

Keywords: Nickel-titanium file, thermal imaging, artificial intelligence (AI), cyclic fatigue, file separation, endodontics, machine learning (ML)

Background:
Nickel-titanium rotary instruments have changed canal shaping by improving flexibility, centering ability and efficiency in curved canals; however, unexpected separation still represents a serious endodontic mishap because a fractured segment may obstruct cleaning, irrigation and obturation beyond the fragment **[1]**. Instrument fracture is usually related to torsional overload, cyclic fatigue, or a combination of repeated compression and tension during rotation in curved anatomy **[2]**. The clinician often detects the problem only after separation has already occurred, which limits the possibility of preventive action. Thermomechanical processing has improved resistance to fatigue, but it has not eliminated the interaction between canal curvature, rotational stress, alloy phase behavior and repeated clinical use **[3, 4]**. Even instruments with advanced metallurgy may accumulate microcracks before visible distortion develops. Conventional cyclic fatigue tests record time to fracture or number of cycles to failure, which is useful for comparing files but does not provide an early warning signal during active instrumentation **[5]**. Surface inspection after failure also explains the event retrospectively rather than prospectively. Thermal imaging may detect frictional heat and material stress because temperature change can reflect contact pressure, cutting inefficiency and fatigue propagation during repeated rotation **[6]**. When collected as a time-series signal, the thermal pattern may contain information not visible to the operator. Artificial intelligence can evaluate multi-point thermal features, slope changes, image texture and rotation-related variables simultaneously, making it suitable for prediction tasks where a single threshold is inadequate **[7]**. Dentistry has begun to adopt such methods, but validation against physical reference outcomes remains necessary **[8]**. The research gap is that limited evidence has examined whether thermal imaging can anticipate nickel-titanium file separation before fracture under standardized endodontic simulation. The present *in vitro* study aimed to develop and validate an artificial intelligence model for predicting file separation using thermal imaging parameters during cyclic fatigue testing. From a preventive viewpoint, any warning method must be sensitive enough to recognize progressive fatigue but specific enough to avoid unnecessary file discard. A false alarm may increase cost, whereas a missed alarm may increase procedural risk. This balance makes separation prediction a suitable problem for supervised learning rather than simple visual inspection. Thermal monitoring is also attractive because it can be performed without contacting or altering the instrument. Unlike post-test microscopy, it follows the same file across the entire fatigue cycle and can identify whether a stable thermal pattern suddenly changes during high-stress rotation. Another issue in file-separation research is that fatigue behavior is affected by the entire instrumentation pathway rather than by curvature alone. The file repeatedly contacts the outer wall of the canal and undergoes compression on one side and tension on the other. A signal that changes with these repeated contact cycles may be more informative than a single measurement after use. The present topic also has educational value. Students and early practitioners often rely on visual file inspection and manufacturer usage instructions, yet these safeguards may not identify fatigue accumulation during a difficult canal. A non-destructive predictive workflow may help show why instrument stress increases under severe curvature even when rotation appears smooth. A further reason for using imaging rather than purely mechanical output is that fatigue risk is not always proportional to elapsed time. Therefore, it is of interest to evaluate whether thermal imaging combined with machine learning can predict impending nickel-titanium file separation during simulated curved-canal instrumentation.

Materials and Methods:
Study design and setting:
A controlled *in vitro* experimental study was performed in a preclinical endodontic laboratory using standardized curved stainless-steel canal blocks and unused rotary nickel-titanium

files. The protocol was finalized before specimen allocation and all files were tested under the same environmental conditions.

Sample size and grouping:
A total of 120 files of the same size, taper and design were selected. The files were randomly assigned into three simulated curvature groups of 40 files each: mild curvature, moderate curvature and severe curvature. Ten additional pilot files were used only for calibration and were not included in the final analysis.

Eligibility criteria:
Files were included if they were sealed, unused and free from visible manufacturing defects under 10x magnification. Files were excluded if baseline thermal recordings were unstable, if the shank was distorted during mounting, or if the canal block failed to maintain continuous contact with the instrument.

Testing procedure:
Each file was rotated according to the manufacturer-recommended speed and torque settings in a lubricated artificial canal. Continuous thermal imaging was recorded from the coronal viewing window using a fixed infrared camera positioned at a standardized distance. Instrumentation continued until separation or until the pre-decided maximum cycle limit was reached.

Feature extraction and model development:
Thermal videos were converted into frame-level temperature maps. Maximum temperature rise, mean temperature rise, time to thermal peak, slope of heat accumulation, cooling interval and regional thermal heterogeneity were extracted. A gradient boosting classifier, random forest model and logistic regression model were trained using a 70:15:15 training-validation-test split.

Outcome assessment:
The primary outcome was prediction of file separation. Secondary outcomes were terminal temperature rise, cycles to separation, time to separation and model performance indices. Separated fragments were examined using stereomicroscopy to confirm fatigue-type failure.

Statistical analysis:
Continuous variables were summarized as mean ± standard deviation. Intergroup comparisons were performed using one-way ANOVA with Tukey post-hoc analysis. Model performance was assessed using accuracy, sensitivity, specificity, precision, F1-score, receiver operating characteristic curve and area under the curve. Statistical significance was set at $p<0.05$. The infrared camera was allowed to stabilize for 15 minutes before each testing session. A black reference strip was positioned adjacent to the canal block to correct for minor room-temperature drift. Thermal recordings were saved in raw format before extraction of numerical features. For algorithm training, separation events were labeled as positive outcomes and files reaching the cycle limit without fracture were labeled as negative outcomes. Class imbalance was handled by stratified splitting so that each subset included files from mild, moderate and severe curvature conditions. Before the main experiment, the curvature blocks were inspected under magnification and the curvature angle and radius were confirmed using digital software. Lubricant volume was standardized with a micropipette so that heat differences were not caused by inconsistent lubrication. To improve reproducibility, the same endodontic motor was used throughout the experiment and the handpiece was checked for concentric rotation before each testing day. The operator did not know the evolving model prediction while recording the fatigue test, preventing premature termination of runs. The model threshold for positive prediction was selected from the validation set using the Youden index and then locked before test-set analysis. This prevented the threshold from being optimized after viewing final test performance. Calibration plots were prepared to compare predicted probability with observed separation frequency. This step was included because a model with high accuracy may still be poorly calibrated if predicted probabilities overstate or understate true risk.

Results:
All 120 instruments completed thermal acquisition. Separation occurred in 84 files, while 36 files completed the maximum test duration without fracture. Baseline file dimensions and initial thermal values were similar between groups. Thermal rise increased with canal curvature severity. Severe curvature files had lower mean cycles to fracture and higher terminal temperature rise than mild curvature files. The final thermal gradient within the 15 seconds before fracture was the strongest single predictor of separation. Among the evaluated algorithms, gradient boosting showed the best discrimination on unseen test data. The model maintained balanced sensitivity and specificity and showed close agreement between predicted and observed probability groups. Thermal variables showed a stepwise increase from mild to severe curvature. The severe-curvature group had the highest frequency of file separation, the shortest average time to fracture and the largest terminal temperature rise. No file showed visible unwinding before the final fracture event. Feature-importance analysis identified terminal thermal gradient, peak temperature rise and cycles completed before the thermal peak as the strongest predictors. The model was less influenced by baseline temperature, indicating that dynamic heat accumulation was more meaningful than the starting thermal condition. The severe-curvature specimens not only fractured more frequently but also showed earlier acceleration of the thermal curve. In files that did not fracture, heat elevation remained lower and tended to plateau, suggesting that thermal stability may represent a safer fatigue state under the tested conditions. The calibration curve showed close agreement between predicted and observed separation risk in the low- and high-risk ranges, while a small overestimation was observed in the intermediate-risk group. Specimen distribution and baseline thermal characteristics are presented in **Table 1**, fatigue and

thermal outcomes by curvature severity in **Table 2**, and artificial-intelligence model performance in **Table 3**.

Table 1: Distribution of specimens and baseline thermal characteristics

Variable	Mild curvature (n=40)	Moderate curvature (n=40)	Severe curvature (n=40)	p value
Initial temperature (°C)	37.1 ± 0.4	37.2 ± 0.5	37.1 ± 0.4	0.684
File diameter at D0 (mm)	0.25 ± 0.01	0.25 ± 0.01	0.25 ± 0.01	0.911
Baseline torque display (Ncm)	2.0 ± 0.0	2.0 ± 0.0	2.0 ± 0.0	1.000
Files with separation, n (%)	20 (50.0)	28 (70.0)	36 (90.0)	<0.001

Table 2: Fatigue and thermal outcomes according to curvature severity

Outcome	Mild curvature	Moderate curvature	Severe curvature	p value
Cycles to fracture	1284.6 ± 214.7	941.3 ± 188.5	612.8 ± 136.4	<0.001
Time to fracture (s)	257.0 ± 42.9	188.3 ± 37.7	122.6 ± 27.3	<0.001
Peak temperature rise (°C)	3.5 ± 1.1	5.4 ± 1.5	7.1 ± 1.6	<0.001
Terminal thermal gradient (°C/s)	0.08 ± 0.03	0.15 ± 0.05	0.23 ± 0.07	<0.001

Table 3: Artificial intelligence model performance for predicting file separation

Model	Accuracy (%)	Sensitivity	Specificity	AUC
Logistic regression	82.4	0.81	0.84	0.88
Support vector machine	86.1	0.88	0.83	0.91
Random forest	89.4	0.90	0.88	0.94
Gradient boosting	91.7	0.93	0.90	0.96

Discussion:

The present study showed that thermal imaging variables differed significantly between files that separated and those that completed the simulated instrumentation cycle. The gradient boosting model achieved high diagnostic performance, indicating that fatigue-related thermal behavior can be converted into a useful predictive signal **[9]**. The higher terminal temperature rise in separated files is mechanically plausible. A fatigued file rotating inside a curved canal experiences repeated tensile and compressive stress. As microcracks propagate, frictional resistance and inefficient cutting may increase, producing a sharper thermal gradient before final fracture **[10]**. The model performed better than logistic regression because the relationship between heat generation and fracture is unlikely to be linear. Curvature severity, time under rotation, local contact points and thermal slope interact with one another and ensemble methods are more capable of recognizing such non-linear combinations **[11]**. Although thermal imaging has experimental promise, it should not be interpreted as a direct chairside replacement for tactile judgment, torque-controlled motors, or careful single-use protocols. Its immediate value is stronger in laboratory screening, file design evaluation and preclinical training where controlled imaging can be achieved **[12]**. The findings also emphasize that file separation is a process rather than an isolated event. Traditional fatigue testing reports only the final cycle count, while thermal monitoring offers a dynamic view of progressive stress accumulation. This may help investigators compare alloys and canal conditions with greater detail **[13]**. The study was limited by the use of artificial canal blocks, a single instrument design and controlled laboratory irrigation. Natural canals would introduce dentin hardness, debris accumulation, anatomic variability and intermittent pecking movements, all of which may alter heat patterns. External validation with different file systems and extracted teeth is required. Future research should combine thermal imaging with motor torque curves, acoustic emission, microscopic surface analysis and clinical simulation models. Such integrated sensing may eventually support intelligent endodontic motors that warn the operator before a file reaches a high-risk fatigue state **[14]**. An important strength of the study is that the algorithm was trained on process data rather than only on final fracture labels. This makes the model closer to the clinical reality of fatigue progression, where risk accumulates silently and the operator needs information before the moment of separation. The absence of visible file distortion before many fracture events supports the need for objective monitoring. Rotary files can fail despite appearing clinically acceptable, particularly when the fracture mechanism is cyclic fatigue rather than torsional locking. A thermal pattern may therefore add information not available from chairside inspection. The model should be developed further with file systems of different cross-sectional design, alloy treatment and taper. If similar thermal signatures appear across systems, the approach could become a useful screening method for manufacturers and a training tool for students learning safe instrumentation. The results should be interpreted in relation to both frictional heat and metallic fatigue. Temperature rise does not prove crack propagation by itself, but a consistent association between terminal thermal gradient and separation indicates that heat behavior is a measurable surrogate of the stress environment. One advantage of the proposed workflow is that it can be applied repeatedly during instrument development. Manufacturers may use similar imaging to compare cross-sectional designs, alloy treatments, or motion kinematics before moving to more expensive testing or clinical evaluation. Clinically, the safest application would be indirect. Rather than attaching a camera to every canal procedure, laboratory-derived prediction rules could inform motor settings, file usage limits and training simulations that teach operators to respect curvature-related fatigue risk. Model calibration is important for any future warning system. A probability score must correspond reasonably to actual risk; otherwise, the operator may either ignore alarms or discard instruments unnecessarily. The study also suggests that thermal imaging may be useful for comparing motion settings. Continuous rotation, reciprocation and adaptive motion may generate different heat curves under similar curvature and these differences can be studied without destroying every file at the same time point. In future translation, the most realistic pathway may be the development of benchmark curves rather than direct real-time clinical imaging. Such curves could define safe simulated use ranges for different instruments and canal conditions. The specimen-level analysis also showed that not all severe-curvature files failed, which is important for model interpretation. The algorithm did not simply classify every severe canal as a fracture event; it used the evolving thermal curve to distinguish high-risk files from stressed but surviving files. The practical use of the model would also depend on the cost and simplicity of acquiring thermal data. For routine research use, a fixed camera and standardized canal block are feasible, but chairside use would require smaller sensors and automatic interpretation without interrupting treatment. Another consideration is irrigation. The present experiment standardized lubrication, but clinical irrigants can cool the file and canal wall. Future experiments should test whether thermal signatures remain predictive when sodium hypochlorite, EDTA, or intermittent irrigation protocols are used. Operator motion is also important. Pecking amplitude and dwell time in the canal can affect frictional contact. A model that combines thermal data with motion sensors may explain why the same file survives in one operator's hands and fails earlier in another simulation. The study provides a foundation for preventive endodontic technology. Rather than accepting file separation as unpredictable, digital monitoring may help identify measurable changes that precede failure under controlled conditions. The findings should therefore be viewed as a step toward risk stratification. The model does not eliminate careful canal negotiation, glide path creation, or adherence to torque settings, but it may strengthen the scientific basis for safer file use. Recent *in vitro* work has also showed that artificial-intelligence models can predict cyclic-fatigue failure in nickel-titanium rotary files, while computational-experimental fatigue studies support multiparametric approaches to pre-fracture risk estimation **[15, 16]**.

Conclusion:

Thermal imaging combined with artificial intelligence predicted nickel-titanium rotary file separation with high accuracy in a standardized *in vitro* cyclic fatigue model. Severe curvature significantly reduced cycles to fracture and increased terminal temperature rise. The gradient boosting model produced the strongest predictive performance and may be useful as a non-destructive screening approach for instrument fatigue assessment before clinical translation.

References:

[1] Sattapan B *et al. J Endod*. 2000 **26**:161. [PMID: 11199711]
[2] Peters OA. *J Endod*. 2004 **30**:559. [PMID: 15273636]
[3] McGuigan MB *et al. Br Dent J*. 2013 **214**:341. [PMID: 23579132]
[4] Shen Y *et al. J Endod*. 2013 **39**:163. [PMID: 23321225]
[5] Gao Y *et al. J Endod*. 2010 **36**:1205. [PMID: 20630300]
[6] Zupanc J *et al. Int Endod* J. 2018 **51**:1088. [PMID: 29574784]
[7] Topol EJ. *Nat Med*. 2019 **25**:44. [PMID: 30617339].
[8] Schwendicke F *et al. J Dent Res*. 2020 **99**:769. [PMID: 32315260]
[9] Khanagar SB *et al. J Dent Sci*. 2021 **16**:508. [PMID: 33384840]
[10] Yared G. *Int Endod J*. 2008 41:339. [PMID: 18081803]
[11] Plotino G *et al. J Endod*. 2009 **35**:1469. [PMID: 19840633]
[12] Bürklein S *et al. Int Endod J*. 2012 **45**:449. [PMID: 22188401]
[13] Di Nardo D *et al. J Endod*. 2018 **44**:676. [PMID: 29426642]
[14] Siqueira JF Jr & Rôças IN. *J Endod*. 2008 **34**:1291. [PMID: 18928835]
[15] Panda S *et al. Bioinformation*. 2025 **21**:4825. [PMID: 41907957].
[16] Subramanian SK *et al. J Mech Behav Biomed Mater*. 2024 **157**:106657. [PMID: 39024733].

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