Original Research

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Influence of artificially simulated pulpal temperature on cyclic fatigue resistance of heat treated NiTi files

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Abstract
INTRODUCTION. NiTi rotary files, which have been heat-treated, have shown an increase in the flexibility and cyclic fatigue resistance. But the effect of the changes of intracanal temperature during clinical instrumentation on file performance is not well known.
MATERIALS AND METHODS. NiTi files with heat treatment ($n = 108$) were used (ProTaper Gold, WaveOne Gold, and Reciproc Blue, $n = 60$ each) in a standardized artificial canal (angled at 60 and radius of curvature = 5 mm). The files were randomly selected into three temperature conditions ($n = 20$ / group): Group A (20°C – room temperature), Group B (37°C – normal body temperature) and Group C (45°C – higher inflammatory temperature). Fatigue test was carried out in a cyclic manner until file fracture. Fracture time (TTF) and cycles to failure (NCF) were measured. One-way ANOVA and Tukey post-hoc tests (0.05) were used in statistical analysis.
RESULTS. A major difference in cyclic fatigue resistance was found across temperature groups in each file system ($p < 0.001$). ProTaper Gold showed 412 ± 68 NCF at 45°C relative to 584 ± 92 at room temperature (20°C) ($p < 0.001$). WaveOne Gold was found to have 738 + 114 NCF at 45°C compared to 1024 + 156 NCF at 20°C ($p < 0.001$). Reciproc Blue used showed 896 ± 128 NCF at 45°C unlike 1246 ± 182 NCF at 20°C ($p > 0.001$). High temperature (45°C) decreased the cyclic fatigue resistance by 28929.5 percent in all the systems subjected to it.
CONCLUSIONS. Artificially reproduced elevated pulpal temperatures have a great influence in reducing cyclic fatigue resistance of heat-treated NiTi files. Endodontic practice requires the clinical awareness of temperature-dependent mechanical behavior to avoid instrument separation and complicate endodontic practice especially in inflamed teeth.

Keywords: cyclic fatigue, heat-treated NiTi, pulpal temperature, rotary files, endodontics, instrument fracture, ProTaper Gold, WaveOne Gold, Reciproc Blue

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Влияние искусственно смоделированной температуры пульпы на сопротивление циклической усталости термообработанных никель-титановых файлов

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Резюме
ВВЕДЕНИЕ. Вращающиеся никель-титановые (NiTi) файлы с термообработкой демонстрируют повышенную гибкость и сопротивление циклической усталости. Однако влияние изменений внутрикоронковой температуры во время клинического инструментирования на характеристики файлов изучено недостаточно.
МАТЕРИАЛЫ И МЕТОДЫ. Для исследования использовались термообработанные NiTi-файлы ($n = 108$): ProTaper Gold, WaveOne Gold и Reciproc Blue (по 60 файлов каждого типа) в стандартизированном искусственном канале (угол изгиба 60°, радиус кривизны 5 мм). Файлы случайным образом распределили по трем температурным условиям ($n = 20$ / группа): группа A – 20°C (комнатная температура);

группа В – 37°С (нормальная температура тела); группа С – 45°С (повышенная воспалительная температура). Испытания на усталость проводились циклически до разрушения файла. Измерялись время до разрушения (TTF) и количество циклов до разрушения (NCF). Для статистического анализа применялись однофакторный ANOVA и post-hoc тест Тьюки (уровень значимости 0,05).
РЕЗУЛЬТАТЫ. В каждой системе инструментов выявлено значительное различие сопротивления циклической усталости между температурными группами ($p < 0{,}001$): ProTaper Gold показал 412 ± 68 NCF при 45°C по сравнению с 584 ± 92 NCF при 20°C ($p < 0{,}001$); WaveOne Gold – 738 ± 14 NCF при 45°C против 1024 ± 156 NCF при 20°C ($p < 0{,}001$); Reciproc Blue – 896 ± 128 NCF при 45°C против 1246 ± 182 NCF при 20°C ($p < 0{,}001$). Повышенная температура (45˚С) снизила сопротивление циклической усталости во всех системах на 28,9–29,5%.
ВЫВОДЫ. Искусственно воспроизведенная повышенная пульповая температура существенно снижает сопротивление циклической усталости термообработанных NiTi-файлов. В эндодонтической практике важно учитывать зависимость механического поведения файлов от температуры, чтобы избегать переломов инструментов и осложнений, особенно при работе с воспаленными зубами.

Ключевые слова: циклическая усталость, термообработанный NiTi, пульповая температура, вращающиеся файлы, эндодонтия, перелом инструментов, ProTaper Gold, WaveOne Gold, Reciproc Blue

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INTRODUCTION

The NIti (Nickel-titanium) rotary and reciprocating tools have transformed the endodontics practice by increasing the effectiveness of shaping, minimizing errors in the procedure, and improving the outcomes of treatment [1]. NiTi alloys have a distinctive superelastic behavior that is caused by stress-induced martensitic transformation, which makes these instruments negotiate intricate root canal anatomy with fewer chances of canal transportation [2]. But then, cyclic fatigue and resulting unexpected separation of instruments is also a major clinical issue, which may become problematic in treatment and undermine prognosis [3].

Cyclic fatigue failure is as a result of repetitive tensile and compressive forces on the rotary instruments in their rotation in curved canals, which eventually causes crack propagation and fracture [4]. The cyclic fatigue resistance depends on a great number of factors such as canal curvature, rotational speed, torque, instrument design, metallurgical property, and manufacturing procedures [5; 6]. Recent developments in the thermomechanical processing have created heat treated NiTi alloys which are more flexible and show increased resistance to fatigue of the cyclic type and superior performance in clinical terms than the traditional NiTi files [7].

The crystallographic phase composition and microstructure of NiTi alloys are altered through heat treatment and the austenite to martensite transformation temperatures are optimized as well as mechanical properties [8]. A number of commercially available heat-treated file systems such as ProTaper Gold (Dentsply Sirona), WaveOne Gold (Dentsply Sirona) and Reciproc Blue (VDW) have been shown to have a higher resistance to cyclic fatigue in laboratory studies [9; 10]. The proprietary thermal processes produce mixtures of austenite, R-phase and martensite at different temperatures, which are basically different mixtures of austenite, R-phase and martensite [11].

Phase transformation temperatures of NiTi alloys are very sensitive to temperature with both mechanical properties strongly depending on environmental temperature [12]. Intracanal temperatures during clinical endodontic treatments can be significantly different to normal body temperature (37°C) because of inflammatory events, exothermic effects during obturation, heat generation by friction during instrumentation, and changes in irrigant temperatures [13]. Past reports have indicated that the levels of temperature have risen as much as 10–15°C higher than physiological levels in inflamed pulpal tissues and even during some endodontic sessions [14].

Although the temperature-dependent nature of NiTi alloys is known, the majority of cyclic fatigue tests assess the behavior of instruments at room temperature (20–25°C), which is not a suitable method to simulate clinical conditions [15]. Little of the evidence has been done on how simulated body temperature has an effect on cyclic fatigue resistance with different findings showing the extent of body temperature effects and its clinical applicability [16]. Besides, the effect of high temperatures that mimic inflammatory or procedurally induced temperature on heat-treated NiTi files is scarcely studied.

The purpose of the in vitro study is to compare and assess the cyclic fatigue resistance of three commercially available heat-treated NiTi file systems (ProTaper Gold, WaveOne Gold and Reciproc Blue) in three artificially simulated pulpal temperature conditions namely, room temperature (20°C), normal body temperature (37°C) and elevated inflammatory temperature (45°C). The null hypothesis is that the simulation of the temperature of the palpali does not have a significant effect on the cyclic fatigue resistance of heat-treated NiTi rotary files.

MATERIALS AND METHODS

Study design and sample size

this experimental in vitro study employed a factorial design with three file systems and three temperature conditions. Sample size calculation was performed using G*Power 3.1 software (Heinrich Heine University, Düsseldorf, Germany), based on pilot study data showing effect size of 0.45, alpha error of 0.05, and power of 0.90, resulting in a minimum requirement of 18 files per group. To account for potential measurement errors and ensure statistical robustness, 20 files per experimental group were allocated, yielding a total sample of 180 files.

Instrument selection

Three heat-treated NiTi file systems were evaluated:

– Group PTG: ProTaper Gold (Dentsply Sirona, Ballaigues, Switzerland) – Size 25, 0.08 taper, 25 mm length;

– Group WOG: WaveOne Gold Primary (Dentsply Sirona) – Size 25, variable taper (0.08–0.03), 25 mm length;

– Group RB: Reciproc Blue R25 (VDW, Munich, Germany) – Size 25, variable taper (0.08–0.03), 25 mm length.

All instruments were inspected under stereomicroscope (Leica M80, Leica Microsystems, Wetzlar, Germany) at 16× magnification to exclude manufacturing defects, deformations, or surface irregularities. Only unused files from the same manufacturing batch were included to minimize variability.

Cyclic fatigue testing apparatus

a custom-designed cyclic fatigue testing device was fabricated following established protocols. The apparatus consisted of a stainless-steel artificial canal with standardized dimensions: 60° angle of curvature, 5-mm radius of curvature, and 1.5-mm internal diameter. The curvature was positioned 5 mm from the file tip, simulating severe clinical canal anatomy. The artificial canal was embedded in a temperature-controlled metal block connected to a precision heating system with digital temperature monitoring (accuracy ±0.2°C).

Temperature simulation protocol

three experimental temperature conditions were established:

– Group A (20°C): Room temperature control, representing standard laboratory testing conditions;

– Group B (37°C): Normal body / pulpal temperature, simulating physiological conditions;

– Group C (45°C): Elevated temperature, simulating inflammatory conditions or procedurally induced thermal elevation.

Temperature stability was maintained using a PID-controlled heating system with continuous monitoring via thermocouples positioned adjacent to the testing canal. Synthetic oil (SAE 15W-40 motor oil) was used as the thermal medium to ensure consistent heat transfer and lubrication, as validated in previous studies. Temperature equilibration was confirmed for 10 minutes before each test sequence.

Testing procedure

Computer-generated randomization (random.org) was applied to assign files randomly to temperature groups. The ProTaper Gold files have been used in constant rotation at 300 rpm with a torque-controlled endodontic motor (X-Smart Plus, Dentsply Sirona). The wave One Gold and Reciproc Blue files were driven in recommended manufacturer counterclockwise reciprocating motions (WOG: 170 50 degrees; RB: 150 30 degrees).

All the files were placed into the artificial canal until the working length (18 mm) was achieved and the constant rotation/reciprocation continued until fracture. The testing apparatus had an automatic stop mechanism which was activated by separation of files. Time to fracture (TTF) was measured in seconds using a digital chronometer and the number of cycles to failure (NCF) was determined using time and rotor/reciprocating speed recorded.

After fracture, all the fragments were then gathered and the length of the fracture was taken using the file tip with the help of the digital caliper (precise to 0.01 mm). Scanning electron microscopy (SEM; JEOL JSM-6610LV, JEOL Ltd., Tokyo, Japan) with a magnification of 500 and 1000 was used to determine fracture surfaces that fractured due to cyclic fatigue and to eliminate torsional fracture.

Data collection and management

all measurements were performed by a single calibrated investigator blinded to the experimental groups. Ten percent of samples were randomly re-measured to assess intra-examiner reliability using intraclass correlation coefficient (ICC). Data were systematically recorded in standardized forms and transferred to electronic spreadsheets for analysis.

Statistical analysis

Statistical analysis was conducted using SPSS version 27.0 (IBM Corporation, Armonk, NY, USA). Normality of data distribution was assessed using Shapiro-Wilk test and visual inspection of Q-Q plots. Homogeneity of variance was evaluated using Levene's test. Descriptive statistics were calculated as means and standard deviations for continuous variables.

Two-way analysis of variance (ANOVA) was performed to evaluate the main effects of file system and temperature, as well as their interaction effect, on cyclic fatigue resistance (NCF and TTF). When significant differences were detected, Tukey's honestly significant difference (HSD) post-hoc test was applied for pairwise comparisons. One-way ANOVA followed by Tukey's test was used for comparisons within each file system across temperature groups. Statistical significance was set at $\alpha = 0.05$.

RESULTS

Reliability and fracture characteristics

intra-examiner reliability demonstrated excellent agreement (ICC = 0.96, 95% CI 0.92–0.98). All files fractured within the curved portion of the artificial canal. Mean fracture lengths were 4.8 ± 0.4 mm for ProTaper

Gold, 4.6 ± 0.5 mm for WaveOne Gold, and 4.7 ± 0.3 mm for Reciproc Blue, with no significant differences between temperature groups ($p = 0.342$). SEM examination confirmed typical cyclic fatigue failure patterns characterized by crack initiation areas and fatigue striations, with no evidence of torsional failure.

Number of cycles to failure (NCF)

Descriptive statistics and comparative analysis of NCF across file systems and temperature conditions are presented in Table 1. Two-way ANOVA revealed significant main effects of both file system ($F = 286.4$, $p < 0.001$) and temperature ($F = 124.8$, $p < 0.001$), along with a significant interaction effect ($F = 3.82$, $p = 0.006$).

Post-hoc comparisons (Tukey HSD): Within each file system, all pairwise temperature comparisons were statistically significant ($p < 0.01$). Between file systems at each temperature, all comparisons showed significant differences ($p < 0.001$).

Time to failure (TTF)

Time to failure results paralleled NCF findings, with significant differences across both file systems and temperature conditions (Table 2).

All pairwise comparisons within file systems across temperatures were significant ($p < 0.01$, Tukey HSD). Between-system comparisons at each temperature showed significant differences ($p < 0.001$).

Percentage reduction in cyclic fatigue resistance

table 3 presents the percentage reduction in NCF at elevated temperatures compared to room temperature baseline, illustrating the magnitude of temperature effects on instrument performance.

The reduction in cyclic fatigue resistance from 20°C to 45°C ranged from 27.9% to 29.5%, with remarkably consistent patterns across all three heat-treated file systems. Each temperature increment (20°C→37°C→45°C) resulted in statistically significant and progressive reduction in fatigue resistance.

Table 1. Number of cycles to failure (NCF) for different file systems at various temperatures

Таблица 1. Количество циклов до разрушения (NCF) для различных систем инструментов при разных температурах

File System	20°C (Group A)	37°C (Group B)	45°C (Group C)	Overall Mean	*F*-value	*p*-value
ProTaper Gold (*n* = 60)	584 ± 92	478 ± 76	412 ± 68	491 ± 102	42.6	< 0.001
WaveOne Gold (*n* = 60)	1024 ± 156	862 ± 128	738 ± 114	875 ± 168	48.2	< 0.001
Reciproc Blue (*n* = 60)	1246 ± 182	1058 ± 148	896 ± 128	1067 ± 208	52.8	< 0.001
Overall Mean	951 ± 298	799 ± 272	682 ± 238	811 ± 282	–	–
F-value	286.4	–	–	–	–	–
p-value	<0.001	–	–	–	–	–

Table 2. Time to failure (TTF) in seconds for different file systems at various temperatures

Таблица 2. Время до разрушения (TTF) в секундах для различных систем инструментов при разных температурах

File System	20°C (Group A)	37°C (Group B)	45°C (Group C)	Overall Mean	*F*-value	*p*-value
ProTaper Gold	116.8 ± 18.4	95.6 ± 15.2	82.4 ± 13.6	98.3 ± 20.4	42.6	< 0.001
WaveOne Gold	246.2 ± 37.5	207.4 ± 30.8	177.6 ± 27.4	210.4 ± 40.4	48.2	< 0.001
Reciproc Blue	299.8 ± 43.8	254.6 ± 35.6	215.6 ± 30.8	256.7 ± 50.0	52.8	< 0.001
Overall Mean	220.9 ± 82.4	185.9 ± 74.8	158.5 ± 64.6	188.5 ± 77.4	–	–

Table 3. Percentage reduction in NCF at elevated temperatures compared to 20°C

Таблица 3. Процентное снижение количества циклов до разрушения (NCF) при повышенных температурах по сравнению с 20°C

File System	37°C vs. 20°C	*p*-value	45°C vs. 20°C	*p*-value	45°C vs. 37°C	*p*-value
ProTaper Gold	−18.2% (106 cycles)	< 0.001	−29.5% (172 cycles)	< 0.001	−13.8% (66 cycles)	0.004
WaveOne Gold	−15.8% (162 cycles)	< 0.001	−27.9% (286 cycles)	< 0.001	−14.4% (124 cycles)	0.002
Reciproc Blue	−15.1% (188 cycles)	< 0.001	−28.1% (350 cycles)	< 0.001	−15.3% (162 cycles)	0.001
Mean across systems	−16.4%	–	−28.5%	–	−14.5%	–

File system ranking

regardless of temperature condition, the rank order of cyclic fatigue resistance remained consistent: Reciproc Blue > WaveOne Gold > ProTaper Gold. At physiological temperature (37°C), Reciproc Blue demonstrated 121% greater fatigue resistance than ProTaper Gold (1,058 vs. 478 cycles, $p < 0.001$) and 23% greater resistance than WaveOne Gold (1,058 vs. 862 cycles, $p < 0.001$).

DISCUSSION

This paper indicates that the artificially created pulpal temperature has a great effect on the cyclic fatigue resistance of heat-treated NiTi rotary files and high temperatures have a great impact on the life of the instruments. The null hypothesis is thus rejected. The ongoing 28–30 per cent reduction in cyclic fatigue resistance in 45°C relative to the room temperature of all the tested file systems is a significant deterioration of the mechanical performance that is clinically meaningful and therefore requires consideration in endodontic practice.

The mechanical behavior of the NiTi alloys under different temperatures is inherently associated with their phase transformation nature [1; 8]. NiTi files that are heat-treated are designed to maximize their metallurgical phases at a certain temperature and the manufacturers aim at a higher martensitic content at the body temperature resulting in better flexibility [7; 11]. This sensitivity to temperature, however, generates a two-sided effect wherein, although flexibility increases come at the cost of canal negotiation, the same decrease in fatigue resistance is known to increase the risk of separation in some situations.

The results of our study are consistent with other studies that have shown a decreased cyclic fatigue resistance at high temperatures [12; 17]. Our study showing a decrease in NCF by approximately 16 percent between 20°C and 37°C also agrees with the findings of de Vasconcelos et al. who recorded 12–18 percent reductions when using conventional NiTi files at the body temperature [16]. But our research builds up on this information by investigating heat-treated alloys and modeling pathologically high temperatures (45°C), a scenario that is often a part of clinical practice in the inflamed pulpal tissues [14].

The physical process which occurs to explain the fact that temperature reduces fatigue resistance has to do with changes in the martensitic transformation of stress induced behavior [8; 11]. When the temperature gets high, the amount of energy needed to change austenite to martensite is higher and the alloy might lose its capacity to mitigate cyclic stress during phase change. Also, increased temperatures can increase the rate of crack propagation and decrease the plastic deformation resistance of the material [18]. The heat treatment processes on proprietary files establish certain austenite finish (af) temperatures, and once the operational temperatures reach the limits of these temperatures, the mechanical properties can be significantly changed [7].

The performance ranking (Reciproc Blue > WaveOne Gold > ProTaper Gold) of the systems under all the temperature conditions indicates that the high cyclic fatigue resistance of some heat-treated systems remains constant regardless of temperatures [9; 10]. This ranking is probably due to variation in heat treatment procedures, metallurgical stages, cross-sectional shape and metal fabrication [11]. Blue thermal treatment according to Reciproc Blue generates more martensite content at body temperature than that of Gold treatment, which may result in greater flexibility and fatigue resistance [10].

Interestingly, both WaveOne Gold and Reciproc Blue which operated in reciprocating motion displayed a higher fatigue resistance than the continually rotating ProTaper gold [9]. Compensating motion also ensures that cumulative stress is minimized through alternate loading of the tensile and compressive surfaces hence increases the life of instruments. This benefit in kinematics seems to be maintained over a temperature condition though the comparative advantage might be counterbalanced by material property variation over temperature.

Our clinical implications of our findings are significant. Pulpal temperatures could be increased during endodontic treatment of teeth with symptomatic irreversible inflammatory hyperemia of the pulp or acute apical periodontitis [14]. Also, on the instrumentation, the friction especially on the calcified or severely curved canals generates heat which can temporarily increase the local temperatures [13]. Such conditions can lead to a situation where instruments will be less fatigue resistant, and risk separation is greatly enhanced. Clinicians should also be more cautious with the instrumentation of inflamed teeth and may use lower insertion forces, reduced progression, and increased file changes.

Refrigerated or room-temperature irrigants may hypothetically counteract fatigue alleviation during temperature, but the practical feasibility and the possible effects on cleaning performance is yet to be explored [13]. In contrast, the presence of the heated irrigants to improve the antimicrobial activity and removal of debris can unintentionally undermine instrument safety which is an element that should be considered when developing a protocol.

It has a number of limitations that should be mentioned. Although the in vitro design allows standardized controlled testing, it cannot completely recreate the complexity of the clinical situation with irregular anatomy of the canal and differences in dentin hardness and variability in technique of the clinician. Synthetic oil as a thermal medium which has been confirmed in the earlier literature is different to the aqueous conditions of sodium hypochlorite irrigation. The artificial canal model used a harsh, though standardised curvature; radii and angles of curvature with different curvature might have various temperature impacts. The temperature was kept constant during each of the tests, and clinical temperatures are dynamic. The evaluations were limited to size 25 instruments; other sizes could exhibit change in sensitivity to temperature because of differences in mass and cross-sectional areas. Lastly, the observation period was relatively short to assess the effects of long-term exposure of temperature to material properties (until fracture).

CONCLUSSION

This in vitro study conclusively indicates that the artificially designed simulated pulpal temperature can have profound effect on cyclic fatigue resistance of rotary files that have been heat treated using NiTi. High temperature (45°C) decreased the cyclic fatigue resistance of the ProTaper Gold, the WaveOne Gold and the Reciproc Blue systems by nearly 28–30 percent relative to room temperature. Even physiological body temperature (37°C) had 15–18 percent reduction in comparison to the normal laboratory testing conditions. The findings imply that fatigue assessment in the conventional cyclic fatigue at room temperature can overestimate the performance of clinical instruments. The fact that the temperature-dependent behaviour is constant over all of the heat-treated systems shows that it is not the system, but a material property phenomenon. Clinicians are encouraged to pay attention to the fact that endodontic instruments working in inflamed teeth or under the conditions that produce frictional heating can have lower levels of fatigue, which should pay more attention to the manifestations of instrument weariness and implement more lenient rules of endodontic instruments. Future studies are needed to determine the interaction between temperature, canal geometry and instrumentation method and the protective interventions including temperature-controlled irrigation procedures. Knowledge about temperature-dependent mechanical behavior is one significant advance in evidence-based instrument selection and use guidelines that can increase patient safety and treatment outcomes.

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