Effect of Environment on Fatigue Failure of Controlled Memory Wire Nickel-Titanium Rotary Instruments

Ya Shen, DDS, PbD, * Wei Qian, DDS, PbD, * Houman Abtin, BDS, * Yuan Gao, DDS, PbD, † and Markus Haapasalo, DDS, PbD *

Abstract

Introduction: This study examined the fatigue behavior of 2 types of nickel-titanium (NiTi) instruments made from a novel controlled memory NiTi wire (CM wire) under various environment conditions. Methods: Three conventional superelastic NiTi instruments of ProFile (Dentsply Maillefer, Ballaigues, Switzerland), Typhoon (Clinician’s Choice Dental Products, New Milford, CT), and DS-SS0250425NEYY (Clinician’s Choice Dental Products) and 2 new CM wire instruments of Typhoon CM and DS-SS0250425NEYY CM were subjected to rotational bending at the curvature of 35° in air, deionized water, 17% EDTA, or deionized water after immersion in 6% sodium hypochlorite for 25 minutes, and the number of revolutions of fracture (Nf) was recorded. The fracture surface of all fragments was examined by a scanning electron microscope. The crack-initiation sites and the percentage of dimple area to the whole fracture cross-section were noted. Results: Two new CM Wire instruments yielded an improvement of >4 times in Nf than conventional NiTi files with the same design under various environments (P < .05). The fatigue life of 3 conventional superelastic NiTi instruments was similar under various environments, whereas the Nf of 2 new CM Wire instruments was significantly longer in liquid media than in air (P < .05). The vast majority of CM instruments showed multiple crack origins, whereas most instruments made from conventional NiTi wire had one crack origin. The values of the area fraction occupied by the dimple region were significantly smaller on CM NiTi instruments than in conventional NiTi instruments under various environments (P < .05). Conclusions: Within the limitations of this study, the type of NiTi metal alloy (CM files vs conventional superelastic NiTi files) influences the cyclic fatigue resistance under various environments. The fatigue life of CM instruments is longer in liquid media than in air. (J Endod 2012;38:376–380)

Key Words

Controlled memory, EDTA, fatigue, nickel-titanium instrument, sodium hypochlorite

The advent of nickel-titanium (NiTi) rotary instruments has revolutionized root canal treatment by reducing operator fatigue and the time required to finish the preparation and minimizing procedural errors associated with hand instrumentation (1). Since their introduction (2), an increasing number of NiTi rotary systems have been marketed by various manufacturers. These systems differ from one another in the design of the cutting blades, body taper, and configuration of the file tip. Despite their increasing popularity, a major concern with the use of NiTi rotary instruments is the possibility of unexpected separation in use (3, 4). Two mechanisms that may lead to NiTi rotary fracture, namely cyclic fatigue and torsional overloading, have been described (5). Cyclic fatigue is a result of rotation around a curve with the consequence of repeated extension and compression of metal and, finally, work hardening followed by fracture (3, 6).

The combination of chelating agents and sodium hypochlorite (NaOCl) has been advocated as an effective irrigation regimen to remove the organic and inorganic matter during the instrumentation phase (7–9). The solution of 17% EDTA was thought to chemically soften the root canal dentin and dissolve the smear layer (8, 9). Additionally, manufacturers of NiTi instruments recommend paste-type EDTA use as a lubricant during rotary root canal preparation, presumably to reduce the risk of instrument separation. The corrosion of endodontic instruments can occur during chemomechanical preparation, cleaning procedures, chemical disinfection, or sterilization (10–13). The fatigue process begins with crack initiation at the material surface. It is well known that environmental conditions can modify both the crack initiation and propagation processes. The resistance to corrosion of root canal instruments could influence their clinical behavior. It is likely that pitting or crevice corrosion might occur initially and then increase the probability of fatigue failure, thereby altering the fracture mechanism from conventional fatigue failure to corrosion failure. Although the corrosion behavior of NaOCl on NiTi instruments has been studied (12–14), the effect of EDTA on the fatigue behavior of superelastic NiTi instruments has not been reported hitherto.

NiTi alloy belongs to the family of intermetallic alloys. This means that alloy can exist in the following various crystallographic forms, with distinct phases and different mechanical properties: austenitic, transformation and martensitic (15). To improve the fracture resistance of NiTi files, manufacturers have developed new manufacturing processes (16–19). Recently, thermal treatment of NiTi alloy is used to optimize the mechanical properties of this alloy (16, 18–23). NiTi rotary instruments (Typhoon...
Materials and Methods

The fatigue testing protocol has been described previously and was reproduced throughout the experimental period (13, 14, 23). Briefly, each NiTi instrument was constrained to a curvature by 3 rigid, stainless-steel pins; a calibrated digital photograph of the curvature was taken. The instrument was then allowed to rotate at 300 rpm (as recommended by the manufacturers) until fracture. The fatigue life, or the total number of revolutions to failure, \( N_f \), was recorded.

NiTi rotary instruments of .04 taper and size 25 ProFile (PF; Dentsply Maillefer, Ballaigues, Switzerland), Typhoon (TYP; Clinician’s Choice Dental Products, New Milford, CT), Typhoon CM (TYP CM; Clinician’s Choice Dental Products), DS-SS0250425NEYY (NEYY; Clinician’s Choice Dental Products), and DS-SS0250425NEYY CM (NEYY CM, Clinician’s Choice Dental Products) were subjected to rotational bending at the curvature of 35° with an 8-mm radius in air (relative humidity, 65%), deionized water, 17% EDTA with a pH of 7.0 (Fisher Scientific, Ottawa, Canada), or deionized water at the temperature of 23° ± 2°C after the working part (16 mm) of the instrument was immersed in 6% NaOCl (Ultra bleach; Shoppers Drug Mart Pharmaprix, Toronto, Canada) at room temperature for 25 minutes. Only a 16-mm length from the tip of the instrument was immersed in the liquid medium during the test to avoid galvanic action between the instrument and its handle. All tested CM wire instruments from Clinician’s Choice Dental Products were prototypes, but according to the manufacturer they are identical with “Typhoon” instruments that will be available soon commercially. Each group included 12 instruments.

After the test, the detached fragment was collected, rinsed briefly with deionized water, and mounted so that the fracture surface was parallel to the microscope stage for detailed examination under scanning electron microscopy (SEM; Stereoscan 260; Cambridge Instruments, Cambridge, UK) operating at 5 to 8 kV. The fracture surface was parallel to the microscope stage for detailed examination under scanning electron microscopy (SEM; Stereoscan 260; Cambridge Instruments, Cambridge, UK) operating at 5 to 8 kV. The fracture surface was parallel to the microscope stage for detailed examination under scanning electron microscopy (SEM; Stereoscan 260; Cambridge Instruments, Cambridge, UK) operating at 5 to 8 kV. The fracture surface was parallel to the microscope stage for detailed examination under scanning electron microscopy (SEM; Stereoscan 260; Cambridge Instruments, Cambridge, UK) operating at 5 to 8 kV. The fracture surface was parallel to the microscope stage for detailed examination under scanning electron microscopy (SEM; Stereoscan 260; Cambridge Instruments, Cambridge, UK) operating at 5 to 8 kV. The fracture surface was parallel to the microscope stage for detailed examination under scanning electron microscopy (SEM; Stereoscan 260; Cambridge Instruments, Cambridge, UK) operating at 5 to 8 kV.

Features of the fracture surface were very similar for both CM wire instruments. The vast majority of CM wire instruments showed multiple crack origins, whereas most instruments made from conventional NiTi wire had one crack origin (Table 2; Fisher exact test, \( P < .05 \)). The values of the area occupied by the dimple region as part of the total surface area of the fractured cross-section were significantly smaller on CM wire NiTi instruments compared with conventional NiTi instruments with the same design under all conditions (Fig. 1; post hoc analysis, \( P < .05 \)). The \( N_f \) was highly correlated with the values of the area occupied by the dimple region \( (r^2 = -0.86) \). None of the tested materials was susceptible to pitting or crevice corrosion in aqueous media (water, 17% EDTA, or water after immersion in 6% NaOCl for 25 minutes) as evaluated under SEM.

Discussion

The main aim of this study was to assess the resistance to cyclic fatigue of the novel CM instruments in various solutions. Clinically, irrigant solutions are stored at room temperature and are used in teeth that have been isolated by rubber dam. Only the working part (16 mm from the tip) of instruments was immersed in solution to avoid galvanic corrosion phenomena that are induced when 2 dissimilar metals are

### Table 1. The \( N_f \) and the Dimple Area/Total Cross-section Area on the Fractured Instrument (%) for Each Brand in Various Environments

<table>
<thead>
<tr>
<th></th>
<th>Air ( N_f )</th>
<th>Dimple area (%)</th>
<th>Water ( N_f )</th>
<th>Dimple area (%)</th>
<th>17% EDTA ( N_f )</th>
<th>Dimple area (%)</th>
<th>Water after immersion in 6% NaOCl ( N_f )</th>
<th>Dimple area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ProFile</td>
<td>641 ± 180</td>
<td>67 ± 8</td>
<td>823 ± 93</td>
<td>68 ± 4</td>
<td>813 ± 112</td>
<td>67 ± 9</td>
<td>801 ± 156</td>
<td>68 ± 6</td>
</tr>
<tr>
<td>TYP</td>
<td>645 ± 232</td>
<td>72 ± 5</td>
<td>620 ± 125</td>
<td>72 ± 2</td>
<td>629 ± 110</td>
<td>75 ± 4</td>
<td>611 ± 111</td>
<td>76 ± 5</td>
</tr>
<tr>
<td>NEYY</td>
<td>1213 ± 430</td>
<td>71 ± 4</td>
<td>1124 ± 208</td>
<td>72 ± 3</td>
<td>1108 ± 257</td>
<td>76 ± 9</td>
<td>1097 ± 244</td>
<td>74 ± 4</td>
</tr>
<tr>
<td>TYP CM</td>
<td>2422 ± 1807</td>
<td>28 ± 6</td>
<td>5689 ± 1170</td>
<td>19 ± 2</td>
<td>9081 ± 791</td>
<td>20 ± 2</td>
<td>5618 ± 786</td>
<td>18 ± 3</td>
</tr>
<tr>
<td>NEYY CM</td>
<td>3491 ± 1783</td>
<td>39 ± 6</td>
<td>7639 ± 1247</td>
<td>31 ± 3</td>
<td>7704 ± 807</td>
<td>31 ± 2</td>
<td>7085 ± 858</td>
<td>32 ± 3</td>
</tr>
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</table>

There was a significant difference in the \( N_f \) and the dimple area/total cross-section between TYP and TYP CM at 4 conditions \( (P < .05) \) and between NEYY and NEYY CM at 4 conditions \( (P < .05) \). There was a significant difference in the \( N_f \) of TYP CM between air with aqueous media \( (P < .05) \). There was a significant difference in the \( N_f \) of NEYY CM between air with liquid media \( (P < .05) \).
coupled in a corrosive electrolyte (25). EDTA was chosen as the medium in which the test was performed to simulate the clinical situation. NaOCl is the most common irrigant used in root canal treatment. NiTi instruments come into contact with NaOCl during disinfection or when the solution is present in the pulp chamber and root canal during instrumentation. NaOCl was found to be highly corrosive to the stainless-steel pins in a pilot study, necessitating very frequent changes of these pins if the test were to be performed in such conditions. During this study and pilot experiments, it was noticed that the fatigue life of CM instruments was around 25 minutes (7,500 cycles) in water. Therefore, the contact time of all NiTi instruments with higher concentrations (6%) was 25 minutes for static immersion before fatigue testing.

The different crystal structures observed in NiTi alloys impart different properties. For instance, the martensite phase is less stiff and more pliable, possessing an elastic modulus of 31 to 35 GPa compared with 84 to 98 GPa for austenite (26). Differential scanning calorimetric analyses have found that the conventional superelastic NiTi wire has the austenite structure at room temperature, whereas CM wire is a mixture of martensite and austenite structure (27). The results of the present study indicated that 2 NiTi instruments made from CM wire were nearly 400% to 600% more resistant to fatigue failure than instruments made from conventional NiTi wire with the same design under various environments. It is consistent with the view that the martensitic form of NiTi has remarkable fatigue resistance; the crack growth in martensite is slower than in austensite and that stress-induced formation of martensite reduces crack growth rate (28).

Both the cross-section factor and material property had a substantial impact on fatigue lifetime (23, 29). This was confirmed by the present findings that square-configuration (ie, NEYY and NEYY CM)
instruments had a significantly longer $N_t$ than triangular-configuration (ie, TYP and TYP CM) instruments under all environments.

The fatigue behavior of NiTi alloys is sensitive to temperature, both locally and environmentally. A function of the aqueous media in metal fatigue behavior is to carry the heat away from the metal-to-metal contact in order to reduce their operating temperature. On repeated loading, the latent heat of the stress-induced martensitic transformation released can elevate the local temperature, leading to a shortened fatigue life (30). The fatigue behavior of conventional superelastic NiTi instruments testing in air produced similar results as those in aqueous media. The short fatigue life (<1,000 cycles) on conventional superelastic NiTi instruments makes the material withstand few load cycles and is not long enough for heat attack. Hence, the absolute number of revolutions survived in aqueous media does not differ much from that in the air for conventional NiTi instruments. On the other hand, an aqueous medium, water or EDTA, would serve as an effective heat sink for the long fatigue life of the CM instrument; the low-cycle fatigue life therein was distinguishable from that in air. Therefore, it may not be surprising that the fatigue life of CM wire instruments in media (from 5,100 to 7,800 cycles [17–26 minutes]) was more than twice as long as that in air (from 2,400 to 3,600 cycles [8–12 minutes]) according to this study. Notice that when NiTi instruments were tested in a dry condition, there was no coolant or lubricant present. The results of the present study indicated that NiTi instruments made from CM wire were nearly 300% to 800% more resistant to fatigue failure than instruments made from conventional NiTi wire in a dry condition. The sources of heat in a dry condition may include friction between the instrument and pins and internal friction from movement of the interface between phases inside the material. This may partly explain that the standard deviations of the fatigue life of CM wire instruments were higher when tested in air than those in liquid media. Also, for the same reason, the mean length of the fractured segment of all instruments in liquid media was more consistent than in air (data not shown).

NiTi alloy has proved to be one of the most biocompatible materials, and it is extremely resistant to corrosion (31). Tobushi et al (32) found that the influence of corrosion fatigue of NiTi wire in water did not appear in the region of low-cycle fatigue. This was confirmed by the present findings. Additionally, a neutral EDTA solution reduces the mineral and noncollagenous protein component of dentin, leading to surface softening but not to erosion of the surface dentin layer during the irrigation (8, 9). The results here indicated that the fatigue lives of all NiTi instruments cycled either under water or 17% EDTA were comparable. These findings are in agreement with previous data (33, 34); the authors attributed the resistance of NiTi in EDTA solution to the ability of EDTA to form the passive film on the metal surface (35). The influence of NaOCl on the corrosion of NiTi instruments has been studied (12–14); despite minor signs of corrosion, they did not appear to involve any significant alteration of the mechanical properties and performance of the instruments. Immersion in 5% NaOCl at a high temperature (37°C and 50°C) for 5 minutes did not reduce the cyclic fatigue resistance of conventional NiTi rotary instruments significantly (36, 37). Such findings lend support to our study here; immersed CM NiTi and conventional NiTi instruments in 6% NaOCl solution for 25 minutes did not reduce the cyclic fatigue fracture resistance. The fractographic appearance of instruments fatigued in NaOCl was very similar to those fatigued in air and water. In addition, no pitting corrosion was formed on the surface (ie, the periphery of the fracture cross-section). The data obtained here cannot be directly extrapolated to clinical conditions. Therefore, conclusions from the present study must be drawn with caution.

The fatigue life of a component can be expressed as the number of loading cycles required to initiate a fatigue crack and to propagate the crack to critical size. With continued cyclic loading, the growth of the dominant crack or cracks will continue until the remaining uncracked section of the component no longer can support the load. At this point, the fracture toughness is exceeded, and the remaining cross-section of the material experiences rapid fracture. This rapid overload fracture is the third stage of fatigue failure, which is occupied by the dimple region. In the present study, the area occupied by the dimple region as part of the total surface area of the fracture cross-section was measured for each specimen. The values of this area were significantly smaller on instruments made from CM wire than on instruments made from conventional NiTi wire. Hence, it is not surprising that CM files had fatigue resistance superior to files made from conventional NiTi alloy.

To our knowledge, this study is the first to focus on the evaluation of fatigue behavior of the novel CM instruments under various environments. Microstructure often plays an important role in controlling the corrosion behavior of materials. The austenitic NiTi was electrochemically more active than the mixture of austenite and martensite (38). However, both NiTi instruments with austenite structure (ie, PF, TYP, and NEYY) and NiTi instruments with a mixture of martensite and austenite structures (ie, TYP CM and NEYY CM) were not susceptible to corrosion in deionized water, deionized water after immersion in 6% NaOCl for 25 minutes, or 17% EDTA at room temperature. Within the limitations of this study, the type of NiTi metal alloy (CM instruments vs conventional superelastic NiTi instruments) influences cyclic fatigue resistance under various environments. The fatigue life of CM instruments is longer in liquid media than in air.

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References


