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Application of non-destructive impedance-based monitoring technique for cyclic fatigue evaluation of endodontic nickel–titanium rotary instruments

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ABSTRACT

This study investigates the application of non-destructive testing based on the impedance theory in the cyclic fatigue evaluation of endodontic Ni–Ti rotary instruments. Fifty Ni–Ti ProTaper instruments were divided into five groups ($n = 10$ in Groups A to E). Groups A to D were subjected to cyclic fatigue within an artificial canal (Group E was the control group). The mean value of the total life limit (TLL), defined as the instrument being rotated until fracture occurred was found to be 104 s in Group A. Each rotary instrument in Groups B, C and D were rotated until the tested instruments reached 80% (84 s), 60% (62 s) and 40% (42 s) of the TLL. After fatigue testing, each rotary instrument was mounted onto a custom-developed non-destructive testing device to give the tip of the instrument a progressive sideways bend in four mutually perpendicular directions to measure the corresponding impedance value (including the resistance and the reactance). The results indicated that the impedance value showed the same trend as the resistance, implying that the impedance was primarily affected by the resistance. The impedance value for the instruments in the 80% and 60% TLL groups increased by about 6 mΩ (about 7.5%) more than that of the instruments in the intact and 40% TLL groups. The SEM analysis result showed that crack striations were only found at the tip of the thread on the cracked surface of the instrument, consistent with the impedance measurements that found the impedance value of the cracked surface to be significantly different from those in other surfaces. These findings indicate that the impedance value may represent an effective parameter for evaluating the micro-structural status of Ni–Ti rotary instruments subjected to fatigue loading.

1. Introduction

The development of rotary nickel–titanium (Ni–Ti) instruments has given rise to new root canal treatment techniques because the pseudo-elasticity properties (shape memory effect and super elasticity) of the instruments limit the failure risk compared with the conventional stainless steel rotary instrument [1–3]. Ni–Ti rotary instruments are manufactured with varying tapers, facilitating the achievement of a funnel-shaped, continuously tapered canal preparation [4]. Many studies have found that preparing canals with rotary Ni–Ti instruments produces an excellent taper, less canal transportation, greater tooth structure conservation and much faster rates than hand instrument [1,2]. However, unexpected fractures in Ni–Ti rotary instruments with no visible signs of previous permanent deformation still occur, even though the rotary instruments are being used within their recommended usable lifetime [5–9].

The major drawback to Ni–Ti rotary instruments is separation during clinical use. These instrument fractures are caused by a combination of torsional and bending fatigue [2,10]. The source of the bending/torsional stresses is the back and forth flexing/twisting load on the instrument that occurs in a cyclic fashion and accounts for 50–90% of the mechanical failures [11]. In fact, complete fracture may occur after a sufficient number of cycles with load variations. However, the magnitude of an individual load excursion may be too small to show any visible damage at all. The damage done involves cumulative micro-structural changes that lead to instrument fracture [11]. Manufacturers suggest discarding the rotary instruments regularly after a certain number of uses. Endodontic experts recommend replacing the rotary instruments after they have been used in very fine, curved or calcified canals to prevent unexpected instrument fractures [5]. However, there are no clear-cut guidelines nor quantitative scientific evidence to suggest under what conditions

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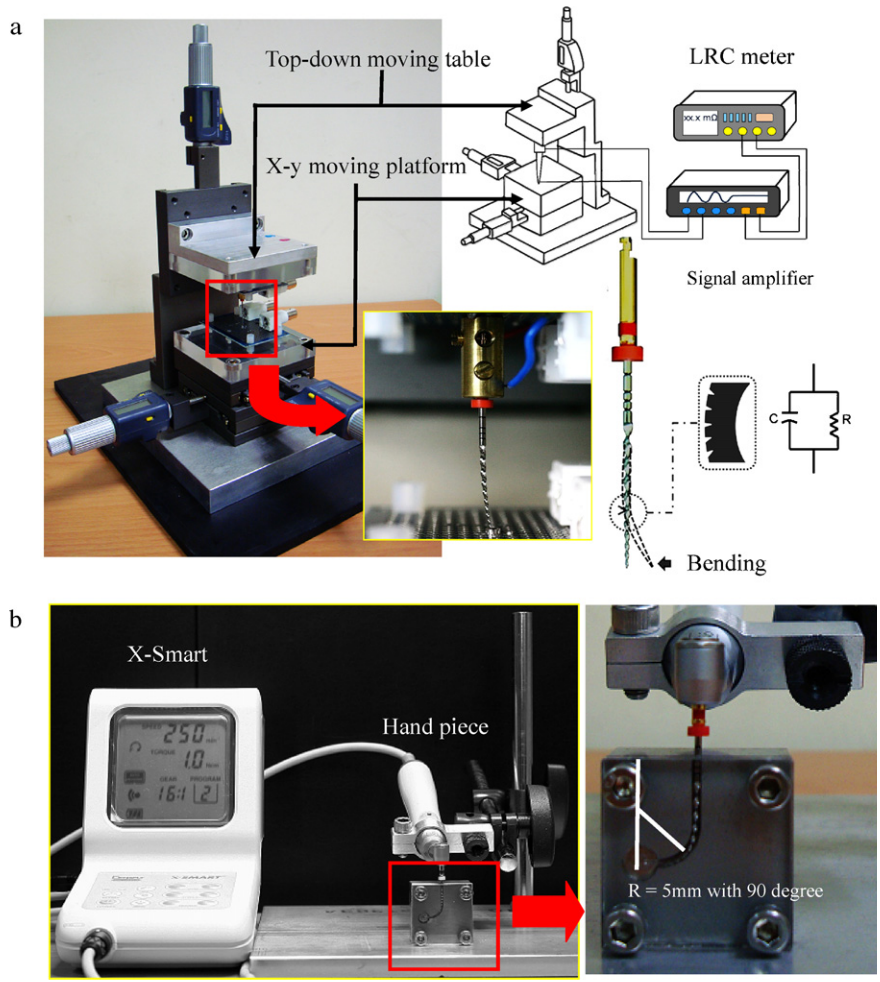

Fig. 1. (a) A custom non-destructive testing device including an *x–y* moving platform, a top-down moving table, an LCR meter and a signal amplifier was assembled to monitor the impedance changes for cyclic fatigue-loaded rotary instruments. The bottom right figure shows that a surface-cracked rotary instrument can be modeled as a capacitor and a resistor connected in parallel. The bottom middle figure shows how the tip of the rotary instrument was progressively bent sideways to measure the corresponding impedance value (including AC resistance and reactance). (b) The left panel shows that a custom-developed fatigue device allowed the instruments to rotate freely inside an artificial stainless steel canal. The right panel shows the artificial canal, which consisted of a concave tempered-steel radius that had a radius of curvature of 5 mm and an angle of 90°.

a rotary instrument should be retired. Therefore, an appropriate method for detecting the remaining life of a used Ni–Ti rotary instrument is needed.

The non-destructive testing concept for detecting Ni–Ti instrument cyclic fatigue has been proposed in recent years. In 2006, Li et al. used Ni–Ti instruments in sloped metal blocks by subjecting them to cyclic fatigue loads through a contra-angle hand piece mounted onto a device used to monitor stiffness with two strain gauges measuring four different directions [5]. The results indicated that prominent stiffness changes were found in three of the 10 tested instruments upon fracturing. Scanning electron microscopy (SEM) evaluation also indicated evidence that crack initiation/propagation occurred near the periphery of the fractured surface. However, the major problem with this technique is that the cracks on the fractured surface might be too small to trigger a sufficient response in the strain gauge-based sensing instrument. The natural frequency (NF) of a mechanical structure is a function of the stiffness and the mass and has been developed as a practical, non-destructive testing technique for detecting the stiffness of metal structures in orthopedic fixation pins and dental implants [8,12–15]. In 2010, Hsieh et al. used NF for monitoring the structural changes in a Ni–Ti instrument during and after the instrumentation process [8]. This study found a significant decrease in the NF (with a decreasing ratio of 5.6%) when the tested instruments reached 77–85% of their total life limit (TLL). However, the NF signals can be easily disturbed by noise in the testing environment, which limits the response accuracy.

An impedance-based monitoring technique was developed and used in various industries to monitor structural damage [16,17]. Any damage to a host structure results in changes to its mechanical impedance, which can be observed by monitoring changes in the electrical impedance value. Therefore, this study investigates whether the impedance-based monitoring technique is a useful approach for detecting the structural status of fatigue-loaded Ni–Ti rotary instruments.

2. Materials and methods

2.1. Impedance-based measured theory

We investigate whether it is possible to evaluate the degree of fracture in endodontic rotary Ni–Ti instruments by measuring their electrical impedance value. The electrical impedance value is the voltage phasor ratio to the current phasor, representing the opposition to current flow in a conductor subjected to an applied voltage.

As shown in Fig. 1, a surface-cracked rotary instrument can be modeled as a capacitor and a resistor connected in parallel. The