The Effect of Surface Defects of HeroShaper Rotary Instruments on the Cyclic Fatigue Fracture: A Fractographic Analysis

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This certifies that the master's thesis of Jung-Kyu Lee is approved.

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감사의 글

먼저 부족한 제가 이 작은 결실을 맺을 수 있도록 이 자리까지 이끌어 주신 하나님께 영광을 돌립니다.

3년간의 보존과 수련 기간 내내 지도와 조언을 아끼지 않으시고 이 논문이 나오기까지 많은 가르침을 주신 금기연 교수님께 감사를 드립니다. 그리고 많은 실습과 세미나를 통해 보존과 수련의로서의 기본과 소양을 갖추고 의국 생활을 지도해 주신 김의성 교수님과 논문에 대해 자세한 지도편달을 아끼지 않으신 치과생체재료공학교실의 김광만 교수님께도 진심으로 감사의 말씀을 드립니다.

수련 생활 동안 진료실 안에서는 보존과 의사로서의 본을 보여 주시고, 진료실 밖에서는 인생의 선배로서 가르침을 베풀어 주신 보존학 교실의 이찬영 교수님, 이승종 교수님, 노병덕 교수님, 박성호 교수님, 정일영 교수님께도 이 지면을 빌어 감사의 말씀을 드립니다.

3년 동안 함께 한 보존과 동기들과 선후배들이 시간이 지날수록 더욱 소중하게 느껴지고 그 귀한 만남에 감사드립니다.

4년 전 한 가정을 이루어 저의 본과 생활부터 늘 제 곁에서, 힘든 날도 기쁜 날도 함께 해 온 남편에게 그때그때 다 표현하지 못했던 제 마음을 전하고 싶습니다. 저를 낳아 주시고 사랑과 정성으로 길러 주신 친정 부모님과 타국에서 힘든 유학 생활 가운데서도 늘 언니, 누나 파이팅을 외쳐 준 동생 명규, 대규에게 사랑한다는 말을 전하고 싶습니다. 아울러 이런 저런 핑계로 며느리 역할에 소홀한 저를 친딸 이상으로 아끼고 보듬어 주시며 격려해 주시는 시부모님께 더욱 기쁨과 자랑이 되는 며느리가 되도록 노력하겠다고 말씀드리고 싶습니다.

2005년 12월 저자 씀

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Abstract

The Effect of Surface Defects of HeroShaper Rotary Instruments on the Cyclic Fatigue Fracture: A Fractographic Analysis

The purpose of this in vitro study was to examine the effect of surface defects of HeroShaper files on the cyclic fatigue fracture in order to determine the failure mechanisms of NiTi instruments by fractographic analysis using scanning electron microscope (SEM). A total of 45 HeroShaper files, 21mm in length with a #30/.04 taper, were divided into three groups containing 15 files each. Group 1 contained new HeroShaper without any defects. Group 2 contained HeroShaper with manufacturing defects such like metal rollover, cracks and flaws. Group 3 contained HeroShaper that had been used for 6-8 root canal treatments by a single endodontist. The test apparatus was designed to allow cyclic tension and compressive stress on the tip of the instrument. The fracture surface of each file was analysed by SEM. There was statistically significant difference in the fracture time between groups 1 and 2, and between groups 1 and 3. However, there was no significant difference between groups 2 and 3. Microphotographs of the lateral surface of the HeroShaper files in Group 2 showed metal rollover and significant machining marks along the faces of the flutes. On the other hand, the lateral surface of the new file was clean and flawless. A low-magnification SEM image of the fractured surface revealed brittle fracture to be the predominant failure mode initially, which typically led to a region of catastrophic ductile fracture in all cases. Qualitatively, the ductile failure region constituted a larger portion of the surface area and was characterized by microvoid formation and dimpling (cup-and-cone fracture). At higher magnification, the brittle fracture region often showed fatigue striations and several secondary cracks, indicating that the following three characteristic stages of fatigue crack growth were present: Stage Ⅰ(initiation), Stage Ⅱ (propagation), and Stage Ⅲ (catastrophic failure). Characteristically, the fractured file surface in group 3 showed evidence of transgranular (cleavage) fracture across the grains, as well as intergranular fracture along the grain boundaries.

These results show that surface defects play important roles in cyclic fatigue fracture, and fractography can be used to analyse fractured NiTi rotary endodontic instruments.

Keywords : Cyclic Fatigue, NiTi File Fracture, HeroShaper, Ductile Fracture, Brittle Fracture, Fractographic Analysis

The Effect of Surface Defects of HeroShaper Rotary Instruments on the Cyclic Fatigue Fracture: A Fractographic Analysis

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Ⅰ. Introduction

Mechanical enlargement of the root canal system is an important part of endodontic treatment. Properly shaped canals are essential for adequate chemical irrigation and ultimately for the proficient hydraulics needed for 3-dimensional obturation (1-3). Recent advances in endodontic instrument design have made proper canal shaping more efficient and predictable. The most noteworthy advance has been the development of nickel-titanium (NiTi) rotary instruments, which have become a mainstay in endodontic and general practice. NiTi rotary instruments are superelastic and far more flexible than stainless steel instruments before exceeding their elastic limit. These superelastic NiTi instruments allow an easier preparation of curved canals whilst minimizing apical transportation. Despite the excellent mechanical properties of this alloy, unexpected fractures as a result of fatigue without any visible signs can occur during its clinical use. Cyclic fatigue has been suggested to account for 50% to 90% of mechanical file fractures (4). Cyclic fatigue is caused by repeated tensile-compressive stress. Rotation subjects an instrument to both tensile and compressive stress in the area of the curve. This repeated tension-compression cycle, which is caused by curved canals, increases the level of cyclic fatigue over time and might be the most important factor in instrument separation (5).

Several studies have examined the factors contributing to instrument distortion and fracture. Of these, the operating revolution per minute (rpm), canal geometry (including the radius and angle of curvature), instrument diameter, cross-sectional area, torque, surface wear and pecking motion have been reported to be most significant (5, 6, 7, 8). However, surface defects such as machining grooves, metal rollover, and flaws left on the cutting blade of an instrument during the manufacturing process can initiate microcracks (9).

A detailed examination of the fractured surface at high magnification is essential for revealing the topographic features that might indicate the underlying mechanism of failure (9). Fractography can be broadly defined as the science of observing, measuring and interpreting fractured surface topography (10). This usually involves an examination of fractured surfaces under different magnifications to identify and measure the relevant features, observe the gross characteristics such as the fracture plane directions. Typically, fractographic analysis can reveal fracture-originating flaws, the direction of crack propagation, and qualitative and quantitative information regarding the stress at failure.

The aim of this in vitro study was to evaluate the effect of surface defects of HeroShaper (MicroMega, Becanson, France) files on the cyclic fatigue fracture and to gain insight into the mechanisms for the failure of NiTi instruments by fractographic analysis using scanning electron microscopy (SEM).

II. Materials & Methods

Materials: A total of 45 HeroShaper files were examined in this study. All the files were 21mm in length and had a #30/.04 taper. They had a non-cutting pilot tip, a positive rake angle, and a variable pitch and helix. The files were divided into three groups of 15 each: Group 1, new HeroShaper files without any defects; Group 2, HeroShaper files with manufacturing defects such like metal rollover, cracks and flaws; and Group 3, HeroShaper files that had been used for 6-8 root canal treatment by a single endodontist.

Experimental Design: The test apparatus was designed to allow cyclic tension and compressive stress on the tip of the instrument whilst maintaining the conditions similar to those experienced in the clinical situations. In addition, the device could be programmed to automatically control rpm, pecking distance, and pecking speed (Fig.1 (a) and (b)). The sloped metal block was fixed to 15° and had a 2mm notched V-form for guiding the instruments. Each file was rotated at 300rpm, with a 6mm pecking distance, and a 1mm/sec pecking speed, respectively. The angle of curvature was 51°, which was calculated using Schneider's method at a 6mm pecking distance (11). Fracture was detected early because the tip of the instrument was visible at the end of the curve of the radii. The time elapsed before fracture was measured using a connected computer program. The files were cleaned ultrasonically in alcohol for approximately 60 seconds prior to the scanning electron microscope (FE SEM, Hitachi S-800, Tokyo, Japan) examination to remove any surface adsorbed debris from the surface. The SEM observations were made with after drying and ion-coating the sample with Eiko IB-C to a 20-30nm thickness. Fractographic analysis was performed by initially surveying the entire fractured surface at low magnification (×100, 200, 500). This usually showed one or more areas where the fracture appeared to have originated. These areas were then observed at higher magnifications (×3000, 5000, 8000, 10,000) to examine surface features that are consistent with the different types of failure (i.e., brittle fracture, fatigue crack growth, or ductile fracture). The data was analysed using the Tukey's test at a 95% confidence level.

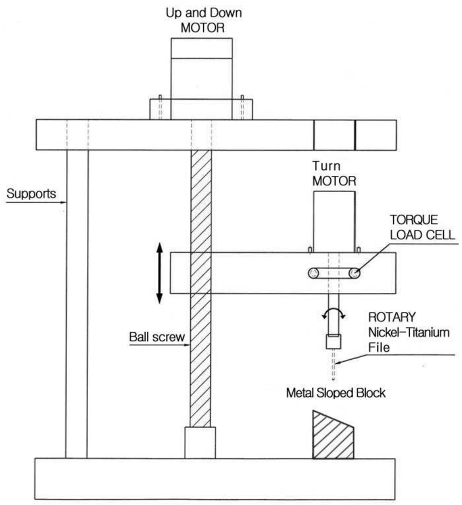

Figure 1 (a) Figure 1 (b)

Figure 1. The test apparatus that automatically controls operation rpm, pecking distance and pecking speed (a), a schematic diagram of Fig. 1 (a) (b).

III. Results

1. Measurement of fracture time under cyclic loading

There was statistically significant difference in the fracture time between groups 1 and 2, and between groups 1 and 3 ($p<0.05$). However, there was no significant difference between groups 2 and 3.

Table 1. Mean time of fatigue failure of the three groups (seconds)

	1	2	3	4	5	6	7	8	9	10	Mean ± SD*
Group 1	618.4	412.4	649.1	529.8	467.7	420.2	376.6	416.6	358.6	455.6	470.5 ± 98.7[a]
Group 2	92.3	412.7	174.5	250.1	394.4	264.6	274.5	467.2	116.0	408.3	285.5 ± 131.8[b]
Group 3	323.6	342.9	318.6	257.6	398.4	275.5	299.6	165.4	120.5	320.8	282.3 ± 83.3[b]

* Statistically significant difference between different letters ($p<0.05$).

2. Fractographic analysis

Microphotographs of the lateral surface of the HeroShaper files show metal rollover (Fig. 2) and significant machining marks along the faces of the flutes (Fig. 3). In contrast, the lateral surface of the new file was clean and flawless (Fig. 4).

Figure 5 shows a typical example of a fractured surface of a HeroShaper instrument that occurred during cyclic bending. A low-magnification (×200)

SEM photomicrograph shows brittle fracture to be the main failure mode initially, which typically led to a region of catastrophic ductile fracture. There was a transition from brittle fracture to ductile fracture in all cases. Qualitatively, the ductile failure region in all the files constituted a larger portion of the surface area and was characterized by microvoid formation and dimpling (cup-and-cone fracture) (Fig. 5 (b)).

At higher magnification (×3000, 10,000), the brittle fracture region often showed fatigue striations and a large number of secondary cracks (Fig. 6 (a), (b)). This suggests that there were three characteristic stages of fatigue crack growth: Stage Ⅰ (initiation), Stage Ⅱ (propagation), and Stage Ⅲ (catastrophic failure). Stage Ⅰ always involves the base of a machining groove and is recognizable pre-existing machining damage (Fig. 7). The distinct zone of ductile dimpling occurs in Stage Ⅲ. Figure 8 shows the brittle fracture region and the transition to ductile failure more clearly.

Typically, the fractured file surface in group 3 showed evidence of transgranular (cleavage) fracture across the grains (Fig. 9), as well as intergranular fracture along the grain boundaries (Fig. 10). Voids or regions of separation between some of the grains were also evident in Figure 9. This suggests the loss of small grains, subgrains, or secondary phase particles during the fracture. Although these types of fractured surfaces correspond to a ductile fracture process, it is distinctively different from the type of fracture shown in Figure 5 (b).

IV. Discussion

This study investigated the effect of surface damages on the fatigue fracture properties of HeroShaper files using a simulated cyclic fatigue device. The mean time of fatigue fracture was group 1>2>3. The reason for group 3 having the lowest time was probably due to the accumulation of internal defects associated with cyclic bending, which were caused by fatigue or torsional overloading while the instruments were being used (12).

Although there was no statistical difference between groups 2 and 3, group 2 showed a larger standard deviation than group 3 (131.8 vs. 83.3), which suggests that a file containing manufacturing flaws is more prone to abrupt fracture when used clinically. Kuhn et. al (13) investigated the microstructural characteristics of NiTi rotary instruments from two different manufacturers. They reported that the instruments before any use revealed a large degree of machining damage, many irregularities and cracks of the instruments. This suggested that the conditions associated with the manufacturing process may play a role in the premature failure on NiTi rotary instruments during clinical use, which is in accordance with the results from the current experiment.

It is evident that the large number of NiTi rotary instruments observed by SEM showed a variety of fracture processes during clinical separation (Fig. 2-9). The fractured HeroShaper instruments generally displayed dimpled rupture features, as shown in Figure 5 (b). These dimples, which were indicative of ductile fracture, were also generally observed on the fracture surfaces of other instruments such as ProFile, ProFile GT, ProTaper etc (14).

Endodontic rotary instruments can fracture as a result of two circumstances: torsional fracture and flexural fatigue. Torsional fracture occurs when the tip or any part of the instrument is locked in a canal while the shaft continues to rotate. The instrument exceeds the elastic limit of the metal resulting in plastic deformation and fracture. The other type of instrument fracture is caused by work hardening and metal fatigue, which results in flexural fracture (failure). With this type of fracture, the instrument is freely rotated in a curved canal. At the point of curvature, the instrument flexes until it fractures at the point of maximum flexure. It is generally believed that this mode of failure is an important factor in the fracture of NiTi rotary instruments. Torsional fracture was reported to occur in 55.7% of all fractured files, whereas flexural fatigue occurred in 44.3% (15). These results suggest that torsional failure, which may be caused by using too much apical force during instrumentation, occurs more frequently than flexural fatigue, which may result from in curved canals.

Dederich et al. (16), who examined stainless-steel instruments in an attempt to significantly extend their instrument life, reported that axial motion (in and out movements) during instrumentation would be expected with NiTi, engine-driven rotary instruments. NiTi instrument manufacturers suggest that these instruments be used with continuous axial motion in the canal. Lingering at a single depth in the canal would closely duplicate the test conditions used in this study, which would significantly reduce the fatigue life of an instrument at a specific point along the instrument shaft (5). Therefore, this mode of operation should be avoided.

The three-stage fracture mechanism of a NiTi file is as follows. Stage I, crack initiation and growth, is characterized by a smooth, almost featureless area at the periphery of the fracture face. Stage Ⅱ, crack propagation, is typified by striations. Each striation represents the progression of a crack caused by tension during a single rotation of the instrument. The fractures propagate from the periphery of the instrument toward the center. Stage Ⅲ, ultimate ductile fracture, can be seen in the center of the fracture surface (5). Stage Ⅰ always involves the base of a machining groove and is recognizable as pre-existing machining damage. This suggests that pre-existing machining defects play role in the cyclic bending fatigue failure mode of NiTi rotary instruments. The distinct zone of ductile dimpling is represented in Stage Ⅲ.

Ductile dimpling is the result of microvoid coalescence and ultimate ductile failure due to a stress state that overwhelms the strength of the material.

This knowledge can be applied to the performance of a more useful fractographic analysis of clinically fractured instruments to determine the level of stress leading to failure in a clinical situation.

The fractographic features of the clinically fractured instruments in this study are consistent with crack propagation (in a brittle fracture mode) from pre-existing machining damage, which transforms to catastrophic ductile failure. This suggests that many premature fractures of NiTi rotary instruments occur (possibly within the elastic limit of the instrument) as a result of crack growth from manufacturing defects.

The SEM observations of the HeroShaper rotary endodontic instruments emphasize the likely role of prominent machining grooves on the surfaces of these instruments in fracture, further noting the special role that embedded dentinal chips have by providing a wedging action on these grooves (17). Generally, the fracture initiation sites of the NiTi files were located at places on the peripheries of the instrument cross-sections where defects from the manufacturing process would provide a concentration of stress. Other studies have reported similar fracture initiation, and emphasized the importance of the surface quality and limited clinical use in avoiding the failure of these instruments.

The fractographic analyses performed in this study provide valuable information on the features expected for instruments that fracture in separate, clinically relevant stress states. The fractographic features observed for fractured NiTi rotary instruments as a result of cyclic fatigue are similar to those reported by Sotokawa for fractured stainless steel hand instruments (18) and to other NiTi rotary instruements (8). However, the findings of this study are in contrast to others that have found only features consistent with ductile failure on the fracture surfaces of instruments fractured in cyclic bending (5, 19). In particular, crack propagation from the surface of instruments, fatigue striations and catastrophic ductile failure was observed.

This knowledge can be applied to perform more useful fractographic analyses of clinically fractured instruments to determine the stress states leading to fracture in the clinical situation.

V. Conclusion

This study evaluated the effect of surface defects of HeroShaper files on the cyclic fatigue fracture using fractographic analysis.

1. There was statistically significant difference in the fracture time between groups 1 and 2, and between groups 1 and 3 ($p<0.05$).
2. All the fractured surfaces showed three characteristic stages of fatigue crack growth, and most areas were found to be ductile in nature suggesting cyclic fatigue to be a major cause of failure.
3. Crack propagation at the grain boundaries and cleavage surfaces indicative of transgranular and intergranular fracture were observed.

These results demonstrate that surface defects play important roles in cyclic fatigue fracture, and that fractography can be used to analyze the fracture mechanics of NiTi rotary endodontic instruments.

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Legends

Figure 1. **The test apparatus that automatically controls operation rpm, pecking distance and pecking speed** (a), **A schematic diagram of Fig.** 1(a) (b).

Figure 2. **Low magnification SEM image of the surface of a HeroShaper file in Group** 2, **showing metal rollover (original magnification,** ×500).

Figure 3. **High magnification SEM image of the surface of a HeroShaper file in Group** 2, **showing significant machining marks along the faces of the flutes associated with the manufacturing process (original magnification,** ×3000).

Figure 4. **SEM image of a new HeroShaper file surface, showing a clean and flawless surface (original magnification,** ×500).

Figure 5. **SEM image of a fractured surface of a HeroShaper file in Group** 1. **A region of brittle fracture** (BF) **is shown originating from the machining groove and subsurface damage. The brittle fracture region transforms to catastrophic ductile failure (DF)** (a). **A high magnification view of the fractured surface of the same file shows elongated dimples (cup-and-cone fracture) that are indicative of ductile fracture. This characteristic feature of ductile failure results from microvoid coalescence as the instrument is subjected to stress (b) (original magnification,** (**a**)×200, (**b**)×3,000).

Figure 6. **High magnification SEM images of the brittle fracture region, showing fatigue striations (arrows) and numerous secondary cracks (original magnification,** (**a**)×3,000, (**b**)×10,000).

Figure 7. **SEM image showing recognizable pre-existing machining damage** (**arrow**) (**original magnification**, ×1,000).

Figure 8. **SEM image of the brittle region** (BF) **and the transition to a ductile failure region** (**original magnification**, ×1,000).

Figure 9. **SEM image of a fractured face of a HeroShaper file in Group** 3, **showing evidence of transgranular** (**cleavage**) **fracture across the grains** (**original magnification**, ×8,000).

Figure 10. **SEM of fractured face of a HeroShaper file in Group** 3, **showing evidence of intergranular fracture along the grain boundaries** (**original magnification**, ×5,000).

Figures

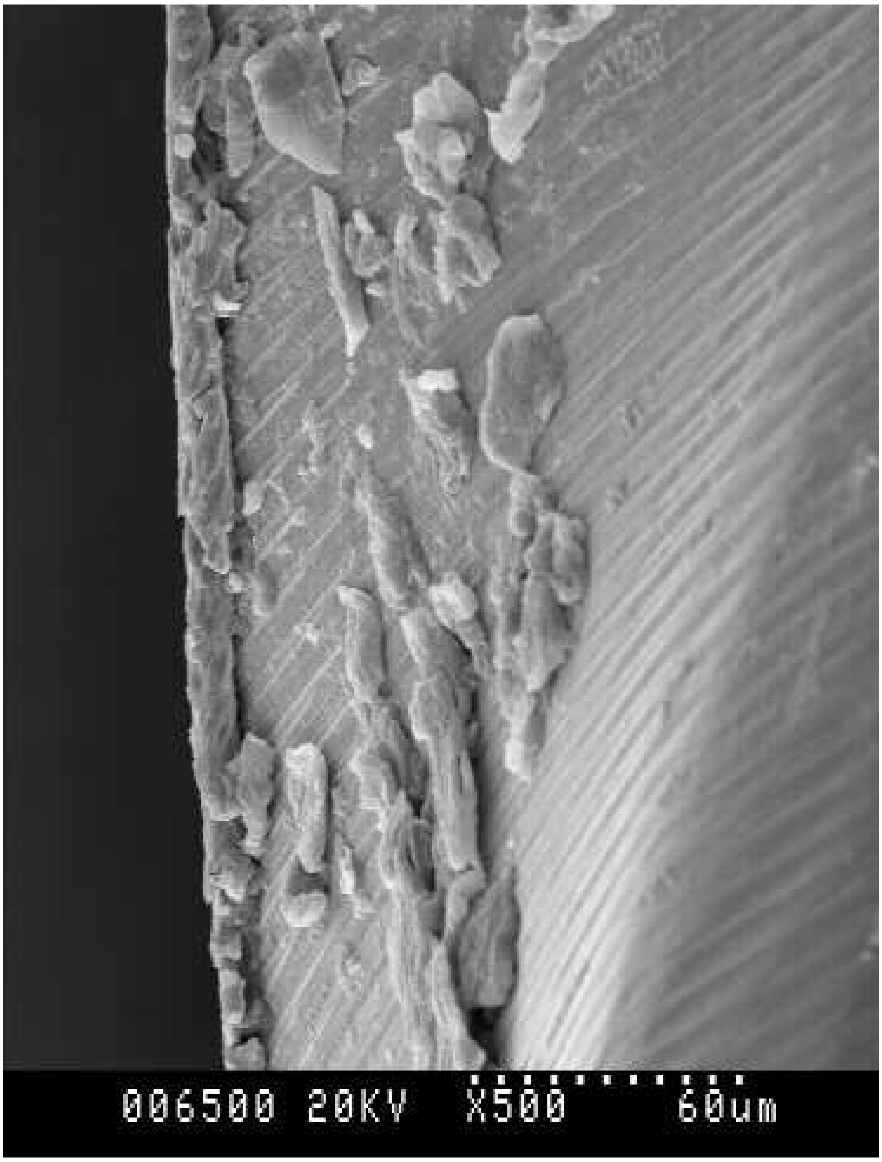

Figure 2

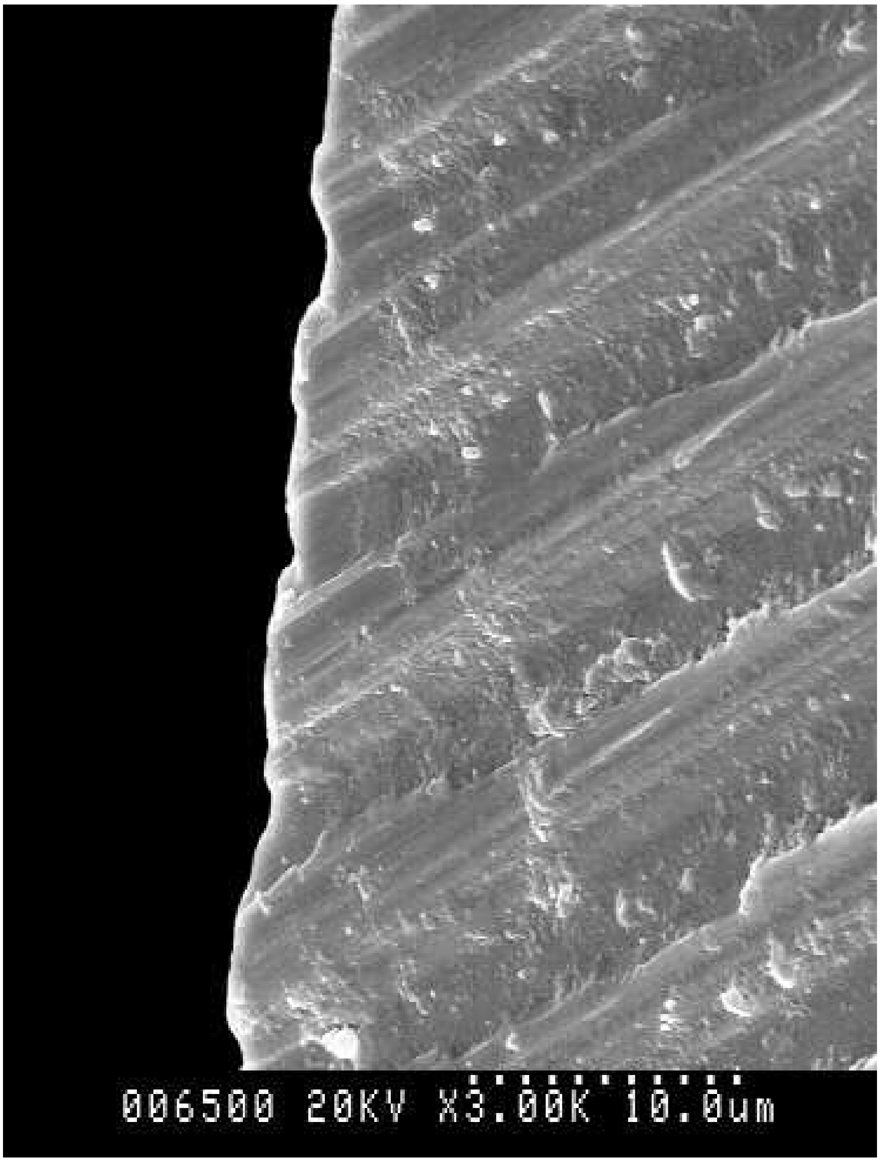

Figure 3

Figure 4

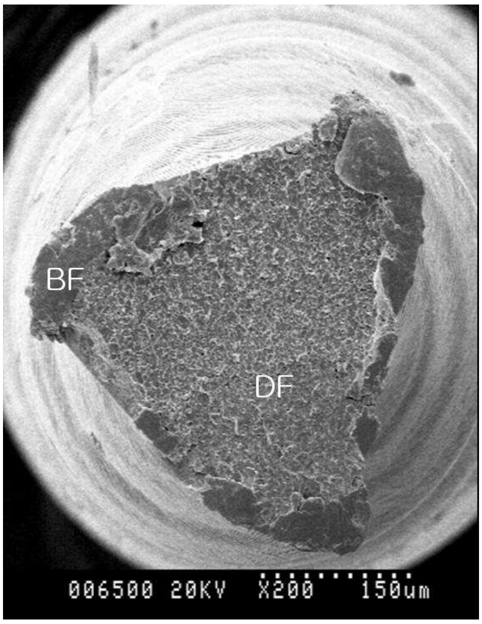

Figure 5 (**a**)

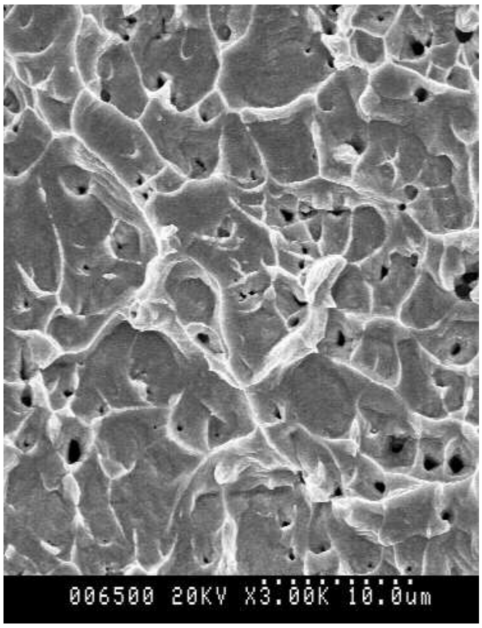

Figure 5 (**b**)

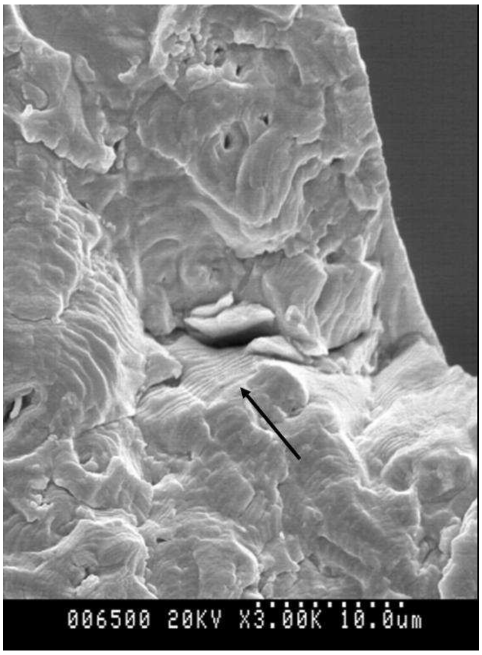

Figure 6 (**a**)

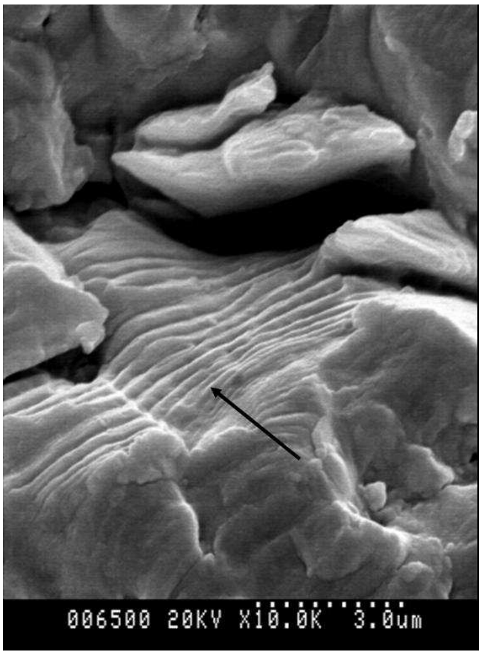

Figure 6 (**b**)

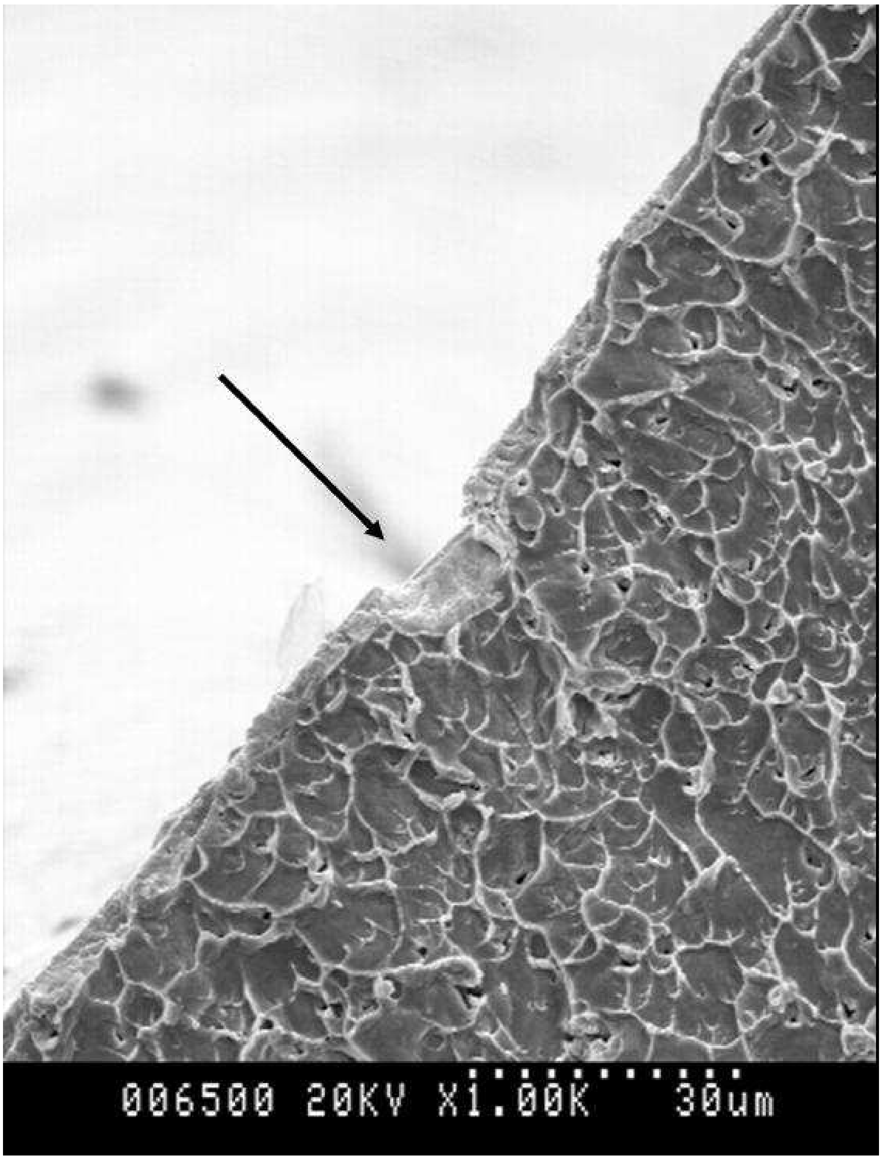

Figure 7

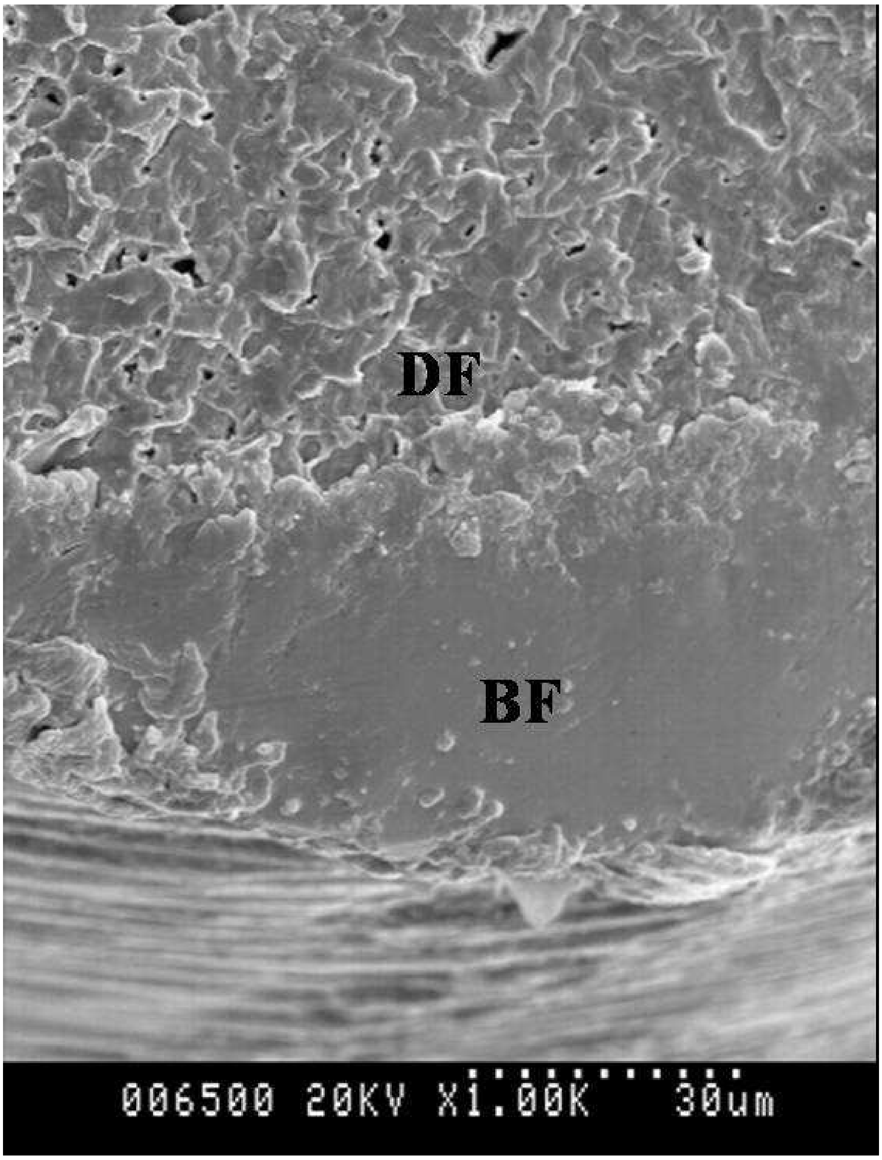

Figure 8

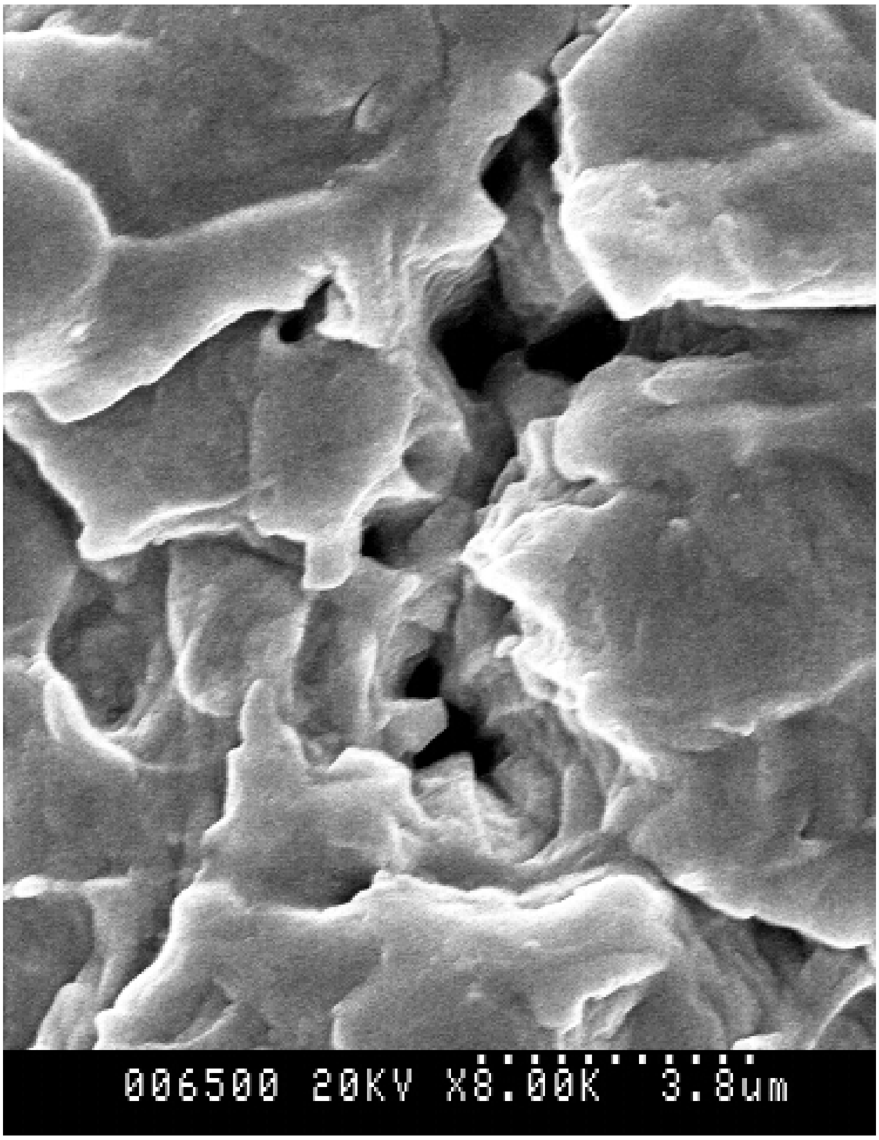

Figure 9

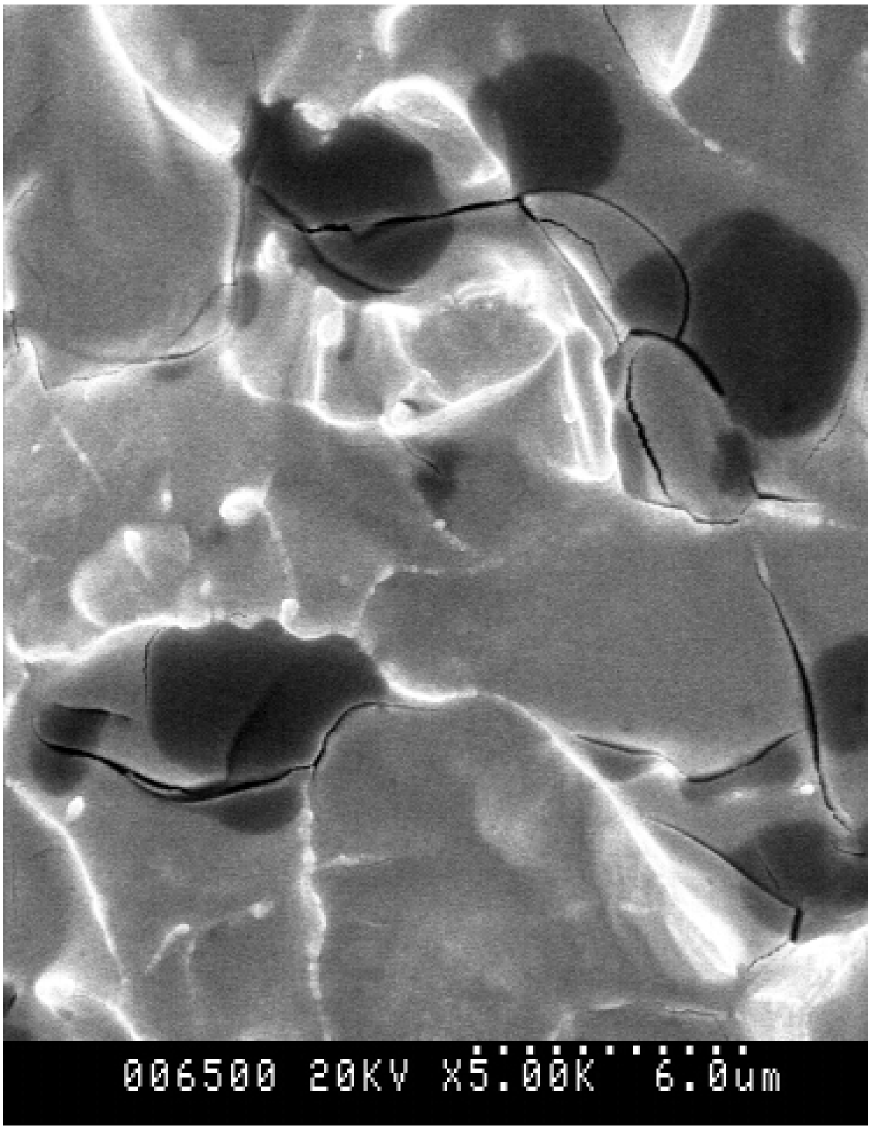

Figure 10

국문 요약

HeroShaper 전동 파일의 반복적 피로 파절에 있어서 표면 결함의 영향: Fractographic 분석

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NiTi file이 근관 치료에 도입된 후, **NiTi**의 초탄성 성질로 인해 만곡된 근관에서 매우 유용하고 효율적으로 사용되고 있다. 그러나 근관 내 사용 도중 특별한 **sign**이 없이 급작스럽게 파절하는 경우가 있어 임상가를 당혹하게 하고, 근관 치료 실패 원인의 하나로 작용하기도 한다. 이번 연구의 목적은 **in vitro** 상에서 반복 피로 파절에 있어서 **HeroShaper files**의 표면 결함의 역할을 평가하고, 파절면을 주사전자현미경을 통해 관찰하여 파절 역학을 규명하는 것이다.

총 45개의 #30/.04 **taper**, 21**mm HeroShaper files**를 사용하였으며, 15개씩 3개의 군으로 분류하여 10개는 반복 피로를 가했고 5개는 표면을 관찰하였다. 제 1군은 결함이 없는 새 **files**, 제 2군은 제조 과정에서 **metal rollover**, **crack**과 같은 결함이 있는 **files**이며 제 3군은 임상에서 6-8개의 근관 성형에 사용된 **files**로 분류하였다. 각 군의 **files**들을 측정 기계를 이용하여 일정한 **rpm**, **pecking distance**, **speed** 하에서 반복 피로를 가하여 파절될 때까지 시간을 측정하여 통계 분석을 하고 단면을 주사전자현미경을 통하여 관찰하였다. 그 결과 파절될 때까지 걸린 평균 시간에 있어서 **group** 1과 2, **group** 1과 3 사이에 통계학적으로 유의할 만한 차이가 있었다. 그러나 **group** 2와 3 사이에는 통계학적인 차이가 없었다. **Fractographic** 분석 결과 파절된 모든 면이 3 단계 (미세 균열 개시, 성

장, 파절)의 특징적 소견과 함께 대부분의 면적에서 연성 파절 양상을 보였다. 표면 관찰 시 **Group 2**에서는 **metal rollover**나 미세 균열과 같은 결함이 발견되었다. 또한 계면에서 **transgranular**와 **intergranular** 파절을 관찰할 수 있었다. 이와 같은 결과로 미루어 보아 표면 결함이 반복 피로 파절에서 중요한 역할을 하며 **fractography** 분석을 통해 **NiTi** 기구의 파절 역학을 규명하는데 응용할 수 있음을 알 수 있다.

핵심 되는 말 : 반복 피로, **NiTi file** 파절, **HeroShaper**, 연성 파절, 취성 파절, **Fractographic** 분석