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Original Article

Force and vibration correlation analysis in the self-adjusting file during root canal shaping: An in-vitro study

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SAF;
Vibration analysis

Abstract *Background/purpose:* The focus of this study was to find a correlation between the forces and vibrations during root canal shaping. This can be used to predict the fracture of the self-adjusting file (SAF) in root canal shaping.

Materials and methods: Forty J-shaped resin blocks were used in this study. Simulated root canals of resin blocks were prepared with the SAF. Force and vibration during root canal shaping were measured by dynamometer and accelerometer respectively. The recorded time domain signal of force and vibration were transformed to frequency domain signals. Frequency domain signals had been used for correlation study between force and vibration amplitude. The root mean square (RMS) value of force and vibration signature for new file and file just before failure were statistically compared using t-test at 95% confidence interval (CI).

Results: Vibrations generated during root canal shaping exhibited positive linear correlation ($r = 0.9173$) with force exerted by the SAF on the root canal. It means vibration has strong correlation with force. The RMS values of force and vibration increase significantly ($P < 0.05$) just before the fracture.

Conclusion: From force and vibration analysis of SAF it was concluded that the vibration is well associated with force applied by the SAF on root canal. Therefore, the trend of force variation was reflected in the vibration signature. The sudden increment in vibration was the symptom of bulge formation and the end of useful life of the SAF.

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Introduction

First root canal instrument was reported in 1838; Edwin Maynard prepared the root canal using a watch spring as shaping file.[1] On the basis of that method, different endodontic instruments were designed, fabricated and used in clinical practice. Dentists have been using nickel-titanium (NiTi) rotary files since 1988.[2] NiTi instruments are more flexible than stainless steel alloy and they are able to go through curved root canal. In order to enhance its performance, the design fabrication and heat treatment process[3] of the endodontic instrument are continuously transforming over the time. Each of new design brings new features and protocols to improve clinical practice. But more or less some typical issues like screwing in, canal deviation and apical transportation are still there with endodontic instruments. To evade the issues related to rotary instruments, the reciprocating instrument was used. However, reciprocation instruments were not able to adequately shape flat root canals.[4] ReDent-Nova (Ra'Anana, Israel) addressed issues such as screw-in effect and shaping of flat root canals in the designing of the self-adjusting file (SAF). The SAF has adjustable, adaptable, thin-walled, hollow pointed cylinder lattice like structure.[4–7] The motion of the SAF is different from other existing instrumentation techniques. The SAF performs in and out oscillatory motion in root canal at the speed of 50 Hz–83.33 Hz instead of continuous angular motion.[4] Root canals with complicated geometry, oval or flat shape cross sections can easily be shaped using the SAF without affecting the original shape and canal integrity, because it does not cut the canal wall.[8]

Apart from its shaping ability, the literature reveals that the SAF loses its filing capability with working time and on further use, the SAF becomes distorted followed by fracture. Different experimental and clinical studies carried out to know about the working and sustainability of the SAF.[9] Reciprocating motion of the SAF generates vibration during root canal shaping. Few studies carried out on these vibrations and comfort[10] condition of patients.[11] This study attempts to investigate vibrations and force generated during root canal shaping using the SAF. Results are shown as time and frequency response. The study shows that frequencies of force and vibration responses are strongly correlated, measured vibrations can be used to predict forces generated during root canal shaping and fracture of endodontic file. This study has clinical relevance to prevent separation of files in the root canal system due to forces exerted on the file, during instrumentation procedures in routine endodontic practice. This may be useful to develop smart endodontic instruments by sensing the amplitude and trend of vibration signature.

Materials and methods

In the present study, forty square pillars, J-shape endodontic training blocks (Endo Training Bloc-J, Dentsply Maillefer, Ballaigues, Switzerland) have been used for force and vibration analysis of the SAF file. Each block was held in a vice to provide a rigid support during experimentation and prevents displacement of the block from its home position. This vice has been mounted on a Kistler dynamometer (Kistler Group, Winterthur, Switzerland) for force measurement. An accelerometer Dytran 3093B (Dytron Corp., Fraser, USA) is used for sensing vibration signals. The accelerometer is mounted on the vice at nearest point to endodontic block, as shown in Fig. 1. Data acquisition frequency for dynamometer and accelerometer are set at 7142 Hz and 51,200 Hz respectively. Sensors are directly connected with data acquisition system, which converts current and voltage signals into respective values of force and acceleration with respect to time. Both data acquisition systems are connected to a computer for online signal monitoring (visualization) and acquisition. Further, force and vibration signals are processed in MATLAB® software developed by MathWorks®, Natick, USA.

The simulated root canals have been prepared by an endodontist having experience of more than five years. Glide path of each endodontic block is verified or established using #15 K file (Dentsply Maillefer, Ballaigues, Switzerland). Each canal is prepared using the SAF file operating at the speed of 5000 oscillations ($\omega_f = 83.33$ Hz) per minute and 0.4 mm amplitude with continuous irrigation of water.The SAF file is used with WaveOne motor (WOM, Dentsply Maillefer, Ballaigues, Switzerland) along with a vibrating hand-piece head (RDT3: ReDent-Nova Reanana, Israel). During canal preparation endodontist manually perform up and down motion (pecking) of the hand-piece.

For real-time monitoring of the SAF during root canal shaping, the separate endodontic file has been used to prepare each root canal. Total forty (n = 40) SAF have been used in this study. The peak amplitude of vibrations and forces correspond to oscillation frequency ($\omega_f = 83.33$ Hz) of the SAF. Responses have been analyzed in frequency domain (FFT of signals) to find correlation between force and vibration. The correlation coefficient between force and vibration amplitude (f and v) is calculated from the following equation.[12]

$$r = \frac{\sum_{i=1}^{n}\left(f_i - \bar{f}\right)(v_i - \bar{v})}{\sqrt{\sum_{i=1}^{n}\left(f_i - \bar{f}\right)^2}\ \sqrt{\sum_{i=1}^{n}(v_i - \bar{v})^2}} \quad (1)$$

For statistical comparison, root mean square (RMS) values of force and vibration signature for normal running

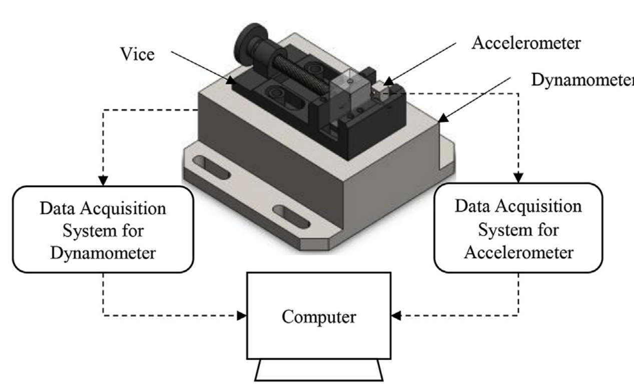

Fig. 1 Schematic diagram of experimental setup.

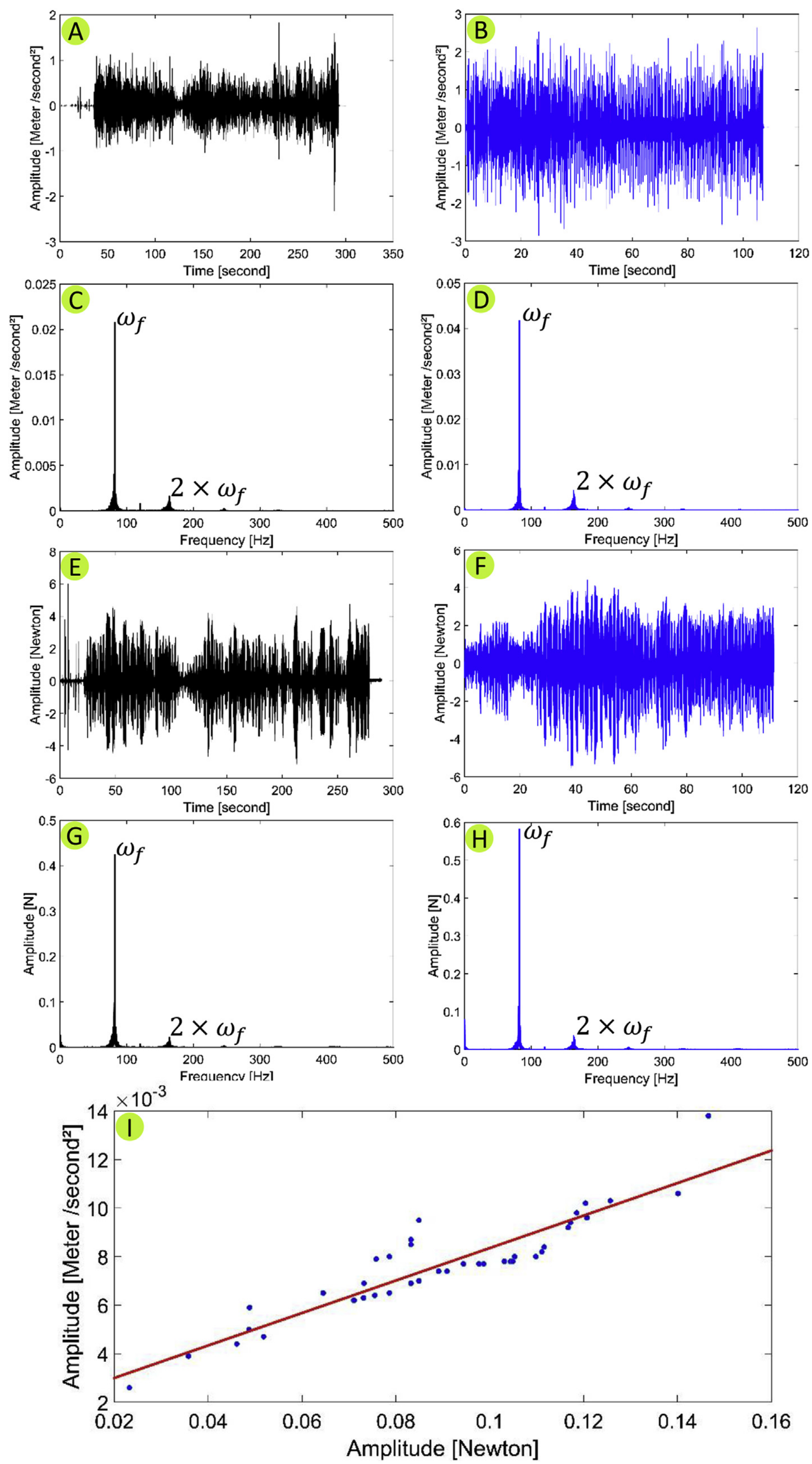

Fig. 2 (A) Vibration signature of healthy file (B) Vibration signature before failure (C) Vibration signature of healthy file in frequency domain (D) Vibration signature before failure in frequency domain (E) Force signature of healthy file (F) Force signature before failure (G) Force signature of healthy file in frequency domain (H) Force signature before failure in frequency domain (I) Positive linear relationship between force and vibration ($r = 0.9173$).

Table 1 Peak amplitude values of force and vibration data of root canal shaping.

Observation (*i*)	Vibration amplitude (A_v)	Force amplitude (A_f)	Observation (*i*)	Vibration amplitude (A_v)	Force amplitude (A_f)
1	0.0084	0.1116	21	0.0062	0.0710
2	0.0047	0.0518	22	0.0080	0.1053
3	0.0062	0.0711	23	0.0096	0.1207
4	0.0078	0.1049	24	0.0074	0.0909
5	0.0059	0.0488	25	0.0080	0.0786
6	0.0087	0.0832	26	0.0102	0.1204
7	0.0044	0.0461	27	0.0065	0.0645
8	0.0082	0.1111	28	0.0026	0.0232
9	0.0106	0.1401	29	0.0085	0.0832
10	0.0039	0.0358	30	0.0070	0.0849
11	0.0077	0.1031	31	0.0065	0.0786
12	0.0094	0.1172	32	0.0078	0.0987
13	0.0064	0.0755	33	0.0050	0.0487
14	0.0098	0.1185	34	0.0138	0.1466
15	0.0079	0.0758	35	0.0092	0.1167
16	0.0063	0.0731	36	0.0076	0.0977
17	0.0078	0.1044	37	0.0080	0.1098
18	0.0095	0.0849	38	0.0103	0.1257
19	0.0069	0.0832	39	0.0077	0.0944
20	0.0074	0.0891	40	0.0069	0.0732

Vibration amplitude in m/sec^2.
Force amplitude in Newton.

Table 2 RMS of force and vibration amplitude of the experimental group (Mean ± Standard Deviation).

Parameters	RMS (Healthy file)	RMS (Before fracture)
Vibration (m/sec^2)	0.1099 ± 0.0082^a	0.2545 ± 0.0188^b
Force (N)	1.0703 ± 0.029^a	1.2344 ± 0.055^b

[a] Different superscript letters in Table 2 indicate significant difference (in horizontal row) between group of normal running and group in which the file get fractured, ($P < 0.05$).
[b] N = Newton; m = metre; RMS = Root Mean Square.

condition and around fracture of the SAF are determined. RMS values are subjected to two sample t-test at 95% confidence interval and calculated using Minitab® 18 (Minitab Inc., Coventry, UK) software.

Results

Force and vibration data are presented as time and frequency responses. Frequency domain signature helps in knowing characteristics frequency and the amplitude of vibrations specifically generated by filing action of the endodontic instrument. Force and vibration responses are shown in Fig. 2. Peak amplitudes from frequency responses of force and vibration are obtained. Peak amplitude values

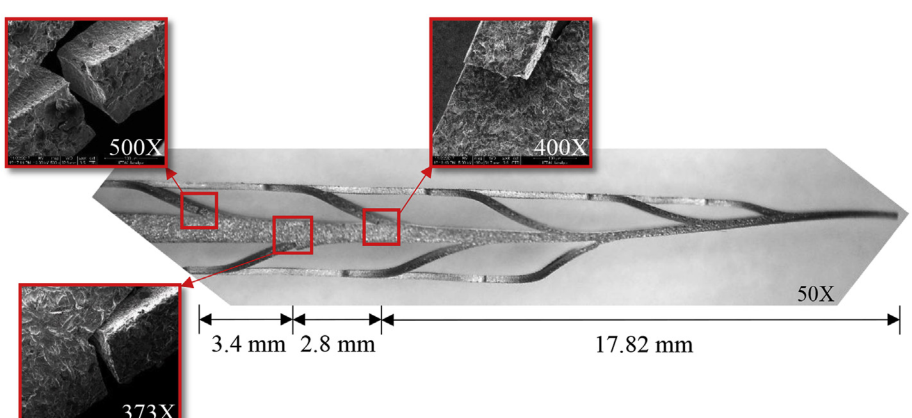

Fig. 3 Image showing fractured branches of SAF after experimentation (inset: zoomed-in SEM image of fracture points).

of force and vibration data are shown in Table 1. To understand relation between force and vibration data, the linear correlation coefficient is determined. The linear correlation coefficient (r) of force and vibration amplitude is 0.9173 which indicate the strong positive linear relationship between them. From these experiments, it has been observed that vibration increases with force during root canal shaping. From the analysis of vibration signals, it is also observed that the amplitude of vibrations are more when file get fractured. Higher amplitudes of force and vibration are observed just before the fracture of the SAF as shown in Fig. 2.

In t-test of parameters, it has been found that there is a significant difference in RMS values of parameters between fractured and healthy file ($P < 0.05$) as shown in Table 2.

Discussion

The SAF oscillates in the longitudinal direction of the root canal during canal shaping. These oscillations are the source of vibration.[9] The SAF has adaptable structure, it shrinks and/or expands in each cycle as per the cross-section of the root canal. Shape adaptability makes its performance different and efficient than other endodontic files.[4] Its lattice has abrasive particles on the upper surface, which erode material from inner wall of the root canal. The SAF perform reciprocating motion at the speed of 5000 oscillations per minute (83.33 Hz). In each stroke of the SAF, small abrasive particles got engaged with resin particles and pulled them from their original position; hence small particles from the inner wall of the root canal are dislodged. For each such stroke of the SAF, force is exerted on root canal which results in vibrations; major amplitudes of vibration occurs at the oscillation frequency ω_f (83.33 Hz) and its harmonics. In other words, the moving file exerts excitation forces on the simulated root canal and therefore system excites on frequency of filing.

During root canal shaping, force may increase to the level which may results in failure of the SAF. Measurement of this force during root canal shaping is a challenging task. The present study analyzes correlation between forces and vibrations during root canal shaping. Correlation coefficient ($r = 0.9173$) indicates that amplitude of force and vibration are strongly related to each other. In each stroke of the SAF, abrasive particles are also grinded along with the erosion of root canal material. After some time, tool blunts due to the continuous grinding of abrasive particles. A blunt tool has less abrasive particles, which results in less amplitude of forces.[9] After certain usage of the SAF, bulging on its lattice has been started. The friction between root canal and the SAF is increased due to bulge formation which causes vibration. Results of t-test ($P < 0.05$) suggest that there is a significant difference between the signature of healthy file and the signature of file just before fracture. Further use of the SAF results in fracture of lattice joints. Before fracture, an increment in force and vibration amplitude is sighted in frequency responses as shown in Fig. 2.

Fig. 3 shows the image of fractured SAF after experimentation. It has been found that the SAF branches are fractured at the junction point and the subsequent fracture is occurred just after previous one. During root canal shaping a reaction force is exerted on the abrasive surface of the SAF[6,13] opposite to the direction of motion. The SAF performed bi-directional linear reciprocating motion in each cycle. In each such cycle, the direction of reaction force vector is transformed by 180° which is the cause of fatigue loading and respective fatigue stress[14] in the SAF. Apart from this, continuous contraction and expansion of the SAF structure in root canal[5,9] is also one of the causes of fatigue stress. These stresses are accumulated at joints of the SAF; which results in fracture of joint.

Earlier studies have revealed that the SAF is safe and efficient for the filing of root canal systems. It was reported that the SAF could be operated for 27 min[4] before any failure but this fact is not universal and may be corresponding to a particular type of canal curvature, dentine properties and operating conditions.[4,7] Akcay et al.[7] revealed that the single SAF may not be enough for curved canal enlargement, particularly for molar tooth with curved root canals, or extra root canal or mesio buccal second or disto buccal second. In such case endodontist needs to change the instrument in between root canal shaping. It is still a complicated task to predict instrument life in during the root canal disinfection. Further, the chances of instrument failure cannot be avoided in clinical practice. In present work, the relation between forces exerted between root canal and the SAF is analyzed. It has been found that forces exerted during root canal disinfection are correlated to the vibration signatures. Vibration signature analysis can be a method for continuous monitoring of the SAF during root canal preparation. Vibration analysis can also be a helpful tool, to estimate structural deformation of file and forces acting during root canal shaping.

Conflicts of interest

The authors deny any conflict of interest related to this study.

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