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Relation between laboratory cantilever bending test and finite element analysis of five different nickel-titanium rotary instruments

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Abstract

Background: Flexibility during bending is a critical feature that influences the performance and safety of endodontic nickel-titanium rotary instruments. Flexibility of the endodontic files could be assessed via laboratory test or indicated theoretically by finite element analysis (FEA). The aim of the study is to determine the cantilever load required for bending five different nickel-titanium (NiTi) rotary instruments (laboratory test) and to calculate maximum von Mises stresses due to bending moment and vertical displacement (deflection) (theoretically by FEA) and compare both results.

Results: TF Adaptive file demonstrates the least cantilever load required for bending, the least von Mises stresses generated and the highest deflection of the endodontic files. Contrary, One Shape file reported the highest cantilever load required for bending, the highest von Mises stresses generated and the least deflection among all the tested endodontic files.

Conclusion: The finite element analysis validated the results of the laboratory cantilever bending test for the examined nickel-titanium rotary instruments.

Keywords: Rotary files, NiTi, Design, Stress distribution, Bending, Flexibility, Deflection, Cantilever bending test, Finite element analysis

Background

The most important objectives of endodontic treatment are to obtain a perfect clean well-shaped root canal and to preserve the root canal anatomy without inducing iatrogenic insults such as ledge formation, canal transportation, or even perforation (Sihivahanan et al. 2017).

The rotational movement of the NiTi rotary instruments inside curved root canals generate both tensile and compressive stresses throughout the sides of the instrument, which should be minimized (Gao et al. 2011). Prevention of instruments fracture during the treatment procedure is mandatory to avoid undesirable clinical situation (Poly et al. 2019). Flexibility during bending and fracture resistance are crucial properties affecting the performance and longevity of the ideal nickel-titanium (NiTi) endodontic rotary instruments (He and Ni 2010; Arbab-Chirani et al. 2011).

Using a flexible NiTi rotary instruments permits their bending ability inside curved canals with minimal load creation. Moreover, it influences the possibility of endodontic file separation (Fukumori et al. 2018). Modifications of the flexibility of the NiTi endodontic rotary instruments depend greatly on their metallurgical composition, fabrication procedure, manufacturing treatment, and geometrical design (He and Ni 2010; Hamdy

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et al. 2019; Galal and Hamdy 2020). Cantilever bending test is the most frequently used test to evaluate the flexibility of the endodontic rotary instruments (Fukumori et al. 2018). The mechanical properties are diverse among the different types of NiTi rotary instruments (Arbab-Chirani et al. 2011).

The NiTi rotary instruments deform permanently when subjected to stresses that exceed the material yield strength with subsequent separation. The increased von Mises stress influences the prospect of instrument segmental separation and consequence failure upon frequent use. It was observed that the stresses upon the NiTi instruments increased with increasing their stiffness (Versluis et al. 2012). Pongione et al. concluded that the increase in Ni-Ti rotary instruments' stiffness results in more stress concentration; therefore, the risk of fatigue failure will increase (Pongione et al. 2012). The displacement of file due to the moment applied to the NiTi rotary instruments varied with the load and bending stiffness linearly (E. et al. 2003).

The FEA approach could be applied to analyze numerically the mechanical behavior of the endodontic instruments. This approach requires construction of a distinct model which coincide with the structure to be investigated and of the mechanical features and composition of the used material; moreover, the environmental conditions should be fixed (E. et al. 2003). The use of FEA investigational method to evaluate the mechanical performance of the dental NiTi instruments appeared to be relevant (Arbab-Chirani et al. 2011).

The behavior of cantilever bending could be simulated in FEA by applying a bending moment to the constructed models and calculating the created equivalent stresses which denotes the three-dimensional stresses condition with a single value, which is called von Mises stress distribution (E. et al. 2003). Moreover, bending displacement (deflection) which is 3 mm from the instrument tip could be also evaluated (Kim et al. 2009a).

Even though FEA is commonly used in the endodontic field to investigate the performance of the NiTi rotary instruments under bending circumstances (Baek et al. 2011; Fu et al. 2019), but up till now a great demand is needed to evaluate the relation between the results of bending the endodontic rotary NiTi instrument experimentally and theoretically by FEA as no previous study compared them.

Therefore, the purpose of the current study was to evaluate the relation between the laboratory cantilever bending test finding and numerical maximum von Mises stresses due to bending moment and deflection values from finite element analysis of five different NiTi rotary instruments.

Methods

Laboratory assessment

The cantilever bending test of five different brands of NiTi rotary instruments were measured using Universal testing machine (Model 3345; Instron Industrial Products, Norwood, MA, USA) to evaluate their flexibility laboratory. The NiTi instruments were divided into five groups (n = 8). All the selected NiTi rotary instruments were with 25-mm length, size 25, and 0.06 taper (Table 1).

Cantilever bending induced at a load-cell of 5 kN. The NiTi rotary instrument specimen was horizontally griped by the tightening screws of the Universal testing machine. The tip of the specimen was subjected to deflection (45°) using mono-beveled chisel attached to the machine upper compartment at cross-head speed (0.5 mm/min). The chisel hit the specimen at 3 mm from the tip of the file as shown in Fig. 1. The maximum load required to bend the specimen was recorded in gram.

Creation of 3-dimensional finite element models

The digitized models of the five brands of NiTi rotary instruments (TF adaptive, HyFlex EDM, Wave one, Reciproc Blue, and One Shape) were created through image processing from real-sized scanning of the actual NiTi rotary instruments via computerized tomography (CT) and stereomicroscope scanning(M. Galal, T. Nassef, S. Saber, M. Zaazou 2015). The C.T. images were obtained using Multi Slice C.T 64 machine (Model GE Discovery VCT, Germany) at 120 kV and 250 mA with thickness slice of 0.4 mm. The NiTi rotary instruments were imaged by a stereomicroscope (Technival 2, Carlzeiss JENA) at magnifications (× 5, × 10, and × 16) to attain the detailed shape.

The collected digitalized images for each file such as cross section, working length, taper, number of flutes, and tip's diameter were utilized to drawn in two-dimensional (2D) models using Computer Aided Design programs (CAD) (SolidWorks software package). The 2D file with (.prt) extension was converted into Stereolithographic (.stl) extension to be readable by MATLAB (MathWorks, Inc., Natick, Massachusetts, USA) software. Building of three-dimensional (3D) model in the form of sections was achieved by MATLAB software using the previous collected imaged data. The 3D models and meshing of the simulated NiTi rotary instruments were done using SolidWorks software (SolidWorks Corp., USA).

Finite element analysis assessment

The assessment of the flexibility of the different finite element models was evaluated mathematically under

Table 1 The NiTi rotary instruments tested

Brand name	Manufacturer	Length	Lot No.
TF Adaptive	SybronEndo, Orange, CA, USA	25	051638929
Hyflex EDM	Coltene/Whaledent, Altstatten, Switzerland	25	H34710
Wave one	Dentsply Maillefer, Ballaigues, Switzerland	25	1098369
Reciproc Blue	VDW, Munich, Germany	25	041332
One Shape	Micro-Mega, Besancon Cedex, France	25	17100107

cantilever bending simulated conditions by applying a constant load of 1 N at 3 mm from the instrument tip (Kim et al. 2009b). The shaft rigidly held in place. Both von Mises stress distribution and vertical displacement (deflection) were recorded in MPa and mm respectively.

Statistical analysis

Statistical analysis was conducted for the laboratory cantilever bending test. A one-way analysis of variance (ANOVA) and a Tukey HSD test were used to perform the statistical analysis using IBM® SPSS® Statistics Version 20 software (SPSS Inc., IBM Corporation; USA). The level of significance was set at 5% ($P < 0.05$).

Results

Laboratory cantilever bending test

Statistical analysis of mean and standard deviation values of the cantilever bending test measured by calculation of the required load to bend the NiTi endodontic instruments to 45° is presented in Table 2 and Fig. 2.

The laboratory finding of the tested endodontic instrument revealed that the TF Adaptive required the least load for cantilever bending (most flexible) (86 g), while the One Shape needed the maximum load for cantilever bending (most stiff) (174 g). The cantilever bending load of the files arranged in an ascending order (g): TF Adaptive (86), HyFlex EDM (99.8), Wave One (144.5), Reciproc Blue (155), and One Shape (174). There was a significant difference between the cantilever bending load among the various endodontic files.

Finite element analysis

Maximum von Mises stress distribution

The von Mises stresses during bending by FEA are shown in Figs. 3, 4, 5, 6, and 7. The TF Adaptive showed the least von Mises stresses (most flexible) (471 MPa), while the One Shape showed the maximum von Mises stresses (most stiff) (1368 MPa). The von Mises stresses of the examined files arranged in an ascending order (MPa): TF Adaptive (471), HyFlex EDM (537), Wave One (583), Reciproc Blue (777), and One Shape (1368). Comparison of the von Mises stress results summarized in bar chart is presented in Fig. 8.

Deflection

The FEA results of the deflection (displacement) displayed that the TF Adaptive showed the maximum deflection (most flexible) (9 mm), while the One Shape showed the least deflection (1.4 mm) (most stiff). The deflection of the tested files arranged in an ascending order (mm): One Shape (1.4), Reciproc Blue (2.3), Wave

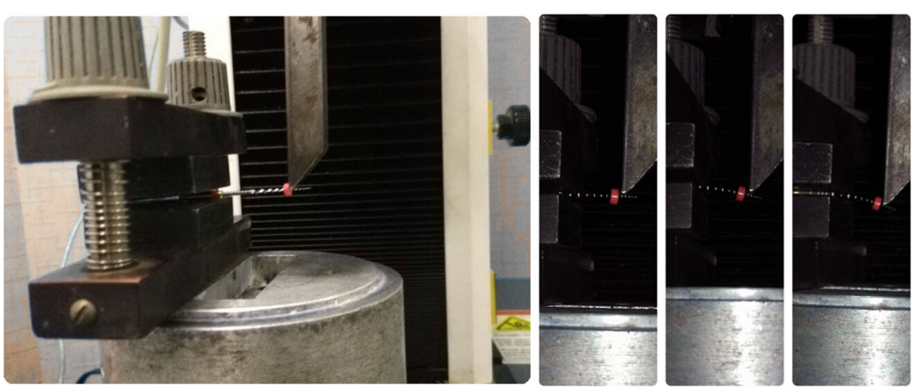

Fig. 1 Laboratory cantilever bending test of NiTi instrument

Table 2 Mean and standard deviation of laboratory cantilever bending test

Endodontic file	TF adaptive		HyFlex EDM		Wave One		Reciproc Blue		One Shape		*P* value
Cantilever bending (grams)	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	˂ 0.0001*
	86[a]	± 0.1	99.8[b]	± 0.5	144.5[c]	± 0.4	155[d]	± 0.8	174[e]	± 0.4	

Mean with different letters indicate statistically significance difference. *Significant ($p < 0.05$)

One (4.5), HyFlex EDM (5.9), and TF Adaptive (9). Comparison of the deflection results summarized in bar chart is presented in Fig. 9.

Finally, the least cantilever load required for bending, the least von Mises stresses generated, and the highest deflection of the endodontic file were detected by using (TF Adaptive). Contrary, the highest cantilever load required for bending, the highest von Mises stresses generated and the least deflection of the endodontic file were detected by using One Shape. Table 3 and Fig. 10 summarize the results obtained from both laboratory cantilever bending test and numerical FEA during bending.

Discussion

The flexibility of NiTi rotary instruments is a decisive requirement for successful root canals treatment, particularly in curved root canals (Gavini et al. 2018). The alloy properties of NiTi rotary instruments dominate their flexibility (Elnaghy and Elsaka 2015). The flexibility is frequently evaluated in the laboratory using cantilever bending resistance test (Zhou et al. 2013). Experimentally, the maximum load required for displacement of the NiTi instrument under cantilever bending moment is a measure of instrument's stiffness. The less the load required to bend the endodontic file indicates the file is more flexible (Kim et al. 2009b).

FEA is a numerical reliable tool to evaluate the stress distribution analyses in the NiTi rotary instruments (Zaazou et al. 2012; Jiang et al. 2018). Moreover, FEA permits the study of each feature individually under controlled conditions. It also allows investigation of different variables that is so difficult to be inspected experimentally (Versluis et al. 2012). Versluis et al. reported that the NiTi rotary instruments' stiffness influences the creation of the internal stresses (Versluis et al. 2012). Deflection under bending reproduces the instrument's flexibility (Galal et al. 2019).

Even though FEA is considered a precisely controlled study, Baek et al. reported that the theoretical FEA results might differ from that of the experimental actual test which may be attributed to the manufacturing methods, surface defects (Baek et al. 2011).

In this study, the relation between the laboratory test and numerical procedure FEA of the rotary NiTi endodontic instrument was evaluated. There is a close relation between the laboratory cantilever bending results and FEA finding gained from both von Mises stress

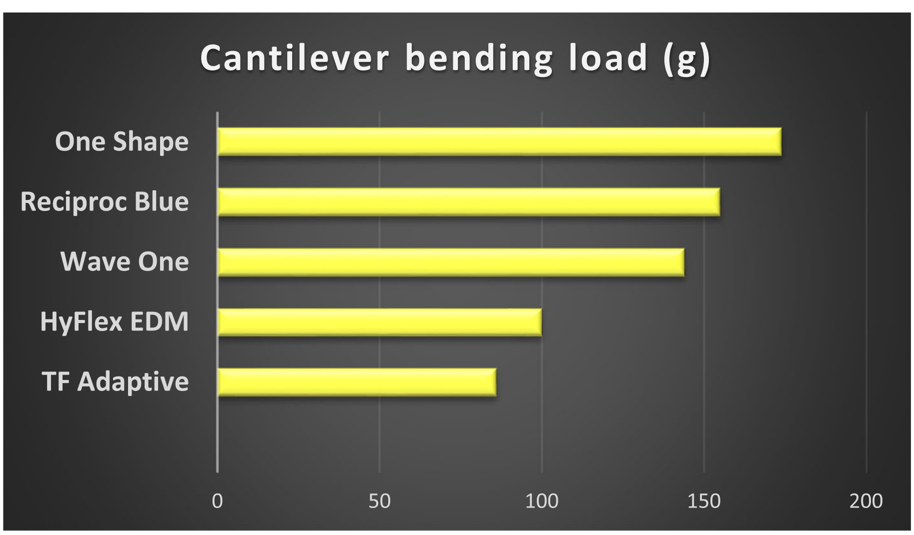

Fig. 2 Bar chart showing cantilever bending load among the different endodontic instruments

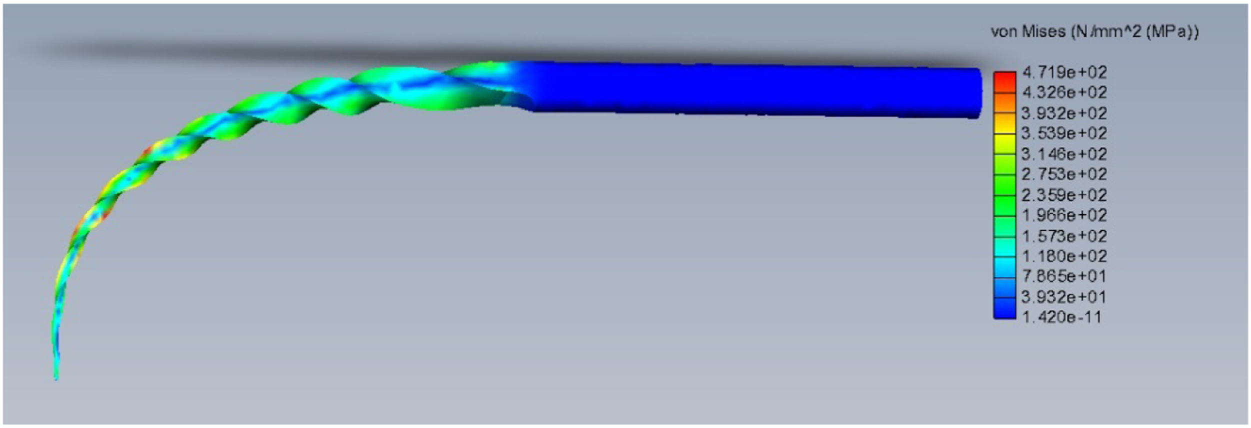

Fig. 3 Von Mises stresses during bending by FEA of TF Adaptive file

distribution and displacement under bending. The matching between laboratory cantilever bending and FEA finding comes in agreement with Lee et al., yet the cyclic fatigue fracture resistance was evaluated in that research (Lee et al. 2011).

The laboratory and numerical finding of TF Adaptive file demonstrate the least cantilever load required for bending, the least von Mises stresses generated, and the highest deflection of the endodontic files which denote their highest flexibility. This finding may be attributed to the metallurgical composition of the file which is based in their fabrication on the transformation of austenite NiTi wire into the R-phase by thermal procedure (De Arruda Santos et al. 2013). Moreover, the twisting of the file give a unique shape that improve file flexibility (Walid 2017; Hamdy et al. 2019).

Contrary, One Shape file reported the highest cantilever load required for bending, the highest von Mises stresses generated and the least deflection among all the tested endodontic files hence decreased flexibility. This may be due to its asymmetrical design with large core diameter which decrease the flexibility of the file (Elnaghy and Elsaka 2015); in addition, the instrument was manufactured through machine grinding to from a conventional austenite (55-NiTi alloy) (Karova 2015).

Thus, the lower the flexibility of the file and the higher cantilever load required for bending were observed; this may produce higher von Mises stress with minimal deflection.

Conclusions

The finite element analysis validated the results of the laboratory cantilever bending test for the examined nickel-titanium rotary instruments. The cantilever bending load varied directly with von Mises stress and inversely with the file deflection and flexibility.

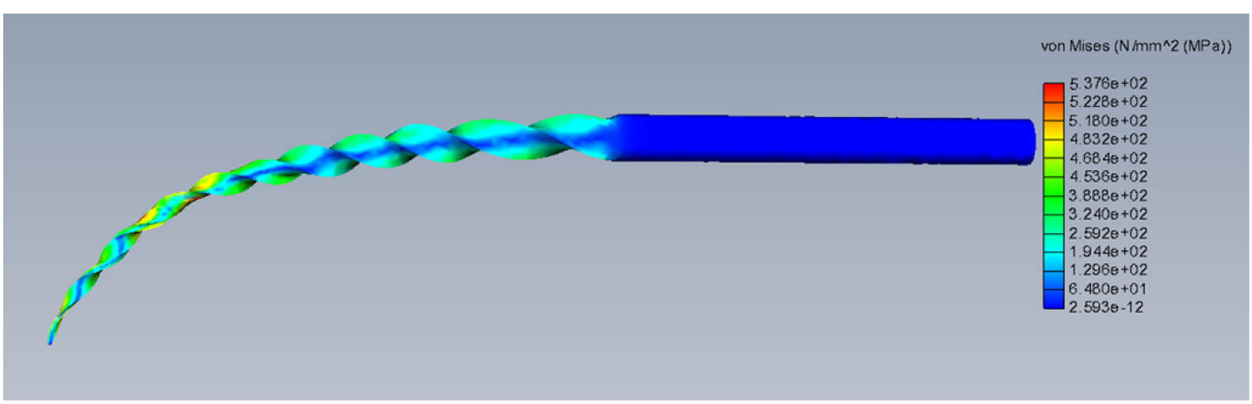

Fig. 4 Von Mises stresses during bending by FEA of Hyflex EDM file

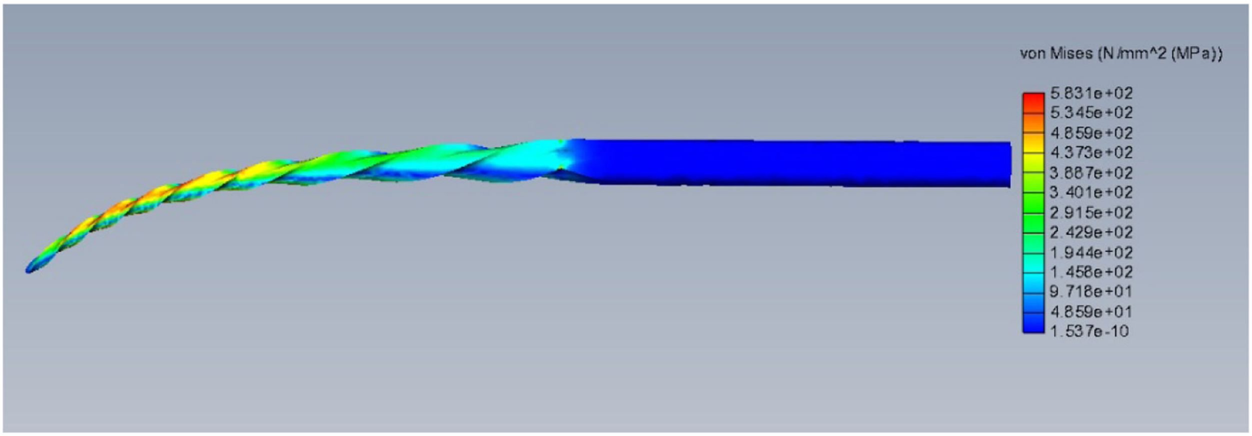

Fig. 5 Von Mises stresses during bending by FEA of Wave one file

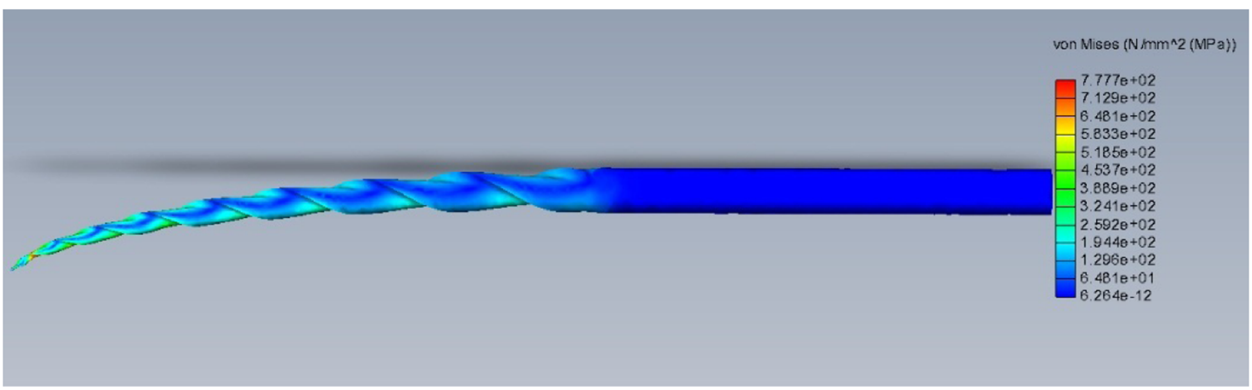

Fig. 6 Von Mises stresses during bending by FEA of Reciproc Blue file

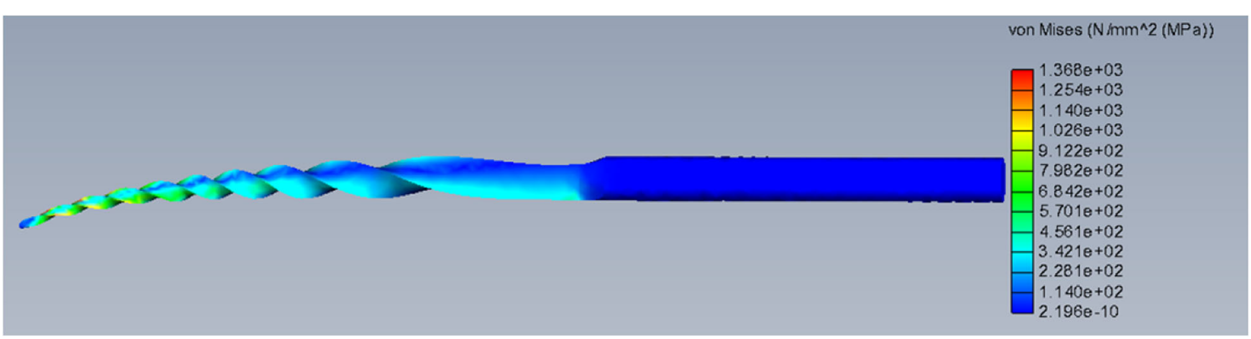

Fig. 7 Von Mises stresses during bending by FEA of One Shape file

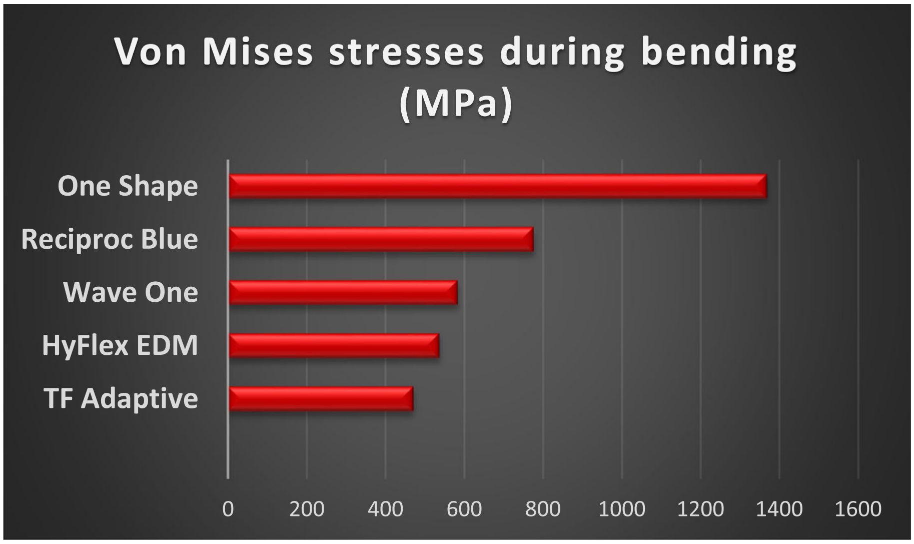

Fig. 8 Bar chart showing von Mises stresses among the different endodontic instruments

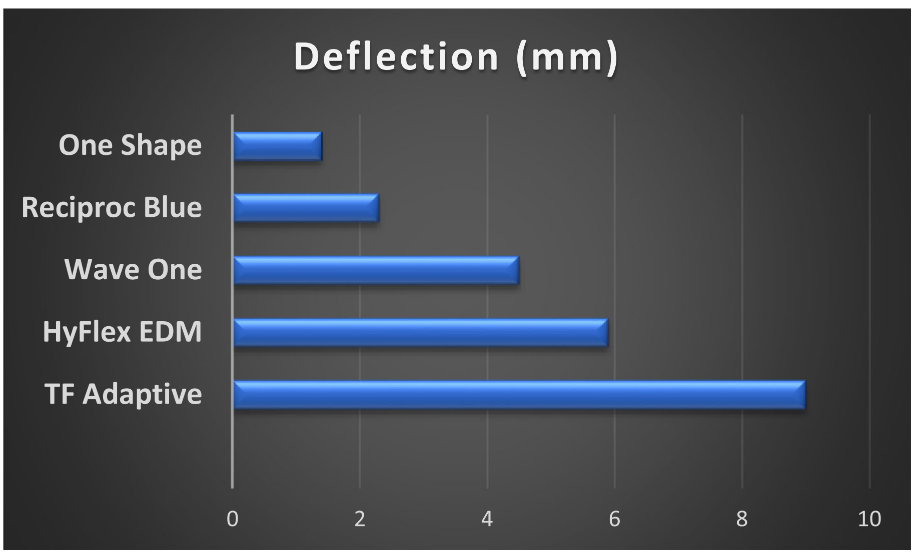

Fig. 9 Bar chart showing deflection among the different endodontic instruments

Table 3 The results of the laboratory cantilever bending test and numerical FEA during bending

Endodontic instrument	Laboratory test	Finite element analysis (FEA)	
	Cantilever bending load (g)	Von Mises stresses during bending (MPa)	Deflection (mm)
TF Adaptive	86[a] ± 0.1	471	9
HyFlex EDM	99.8[b] ± 0.5	537	5.9
Wave One	144.5[c] ± 0.4	583	4.5
Reciproc Blue	155[d] ± 0.8	777	2.3
One Shape	174[e] ± 0.4	1368	1.4
	P value ˂ 0.0001*		

Means with different letters indicate statistical significance difference *significant ($p < 0.05$)

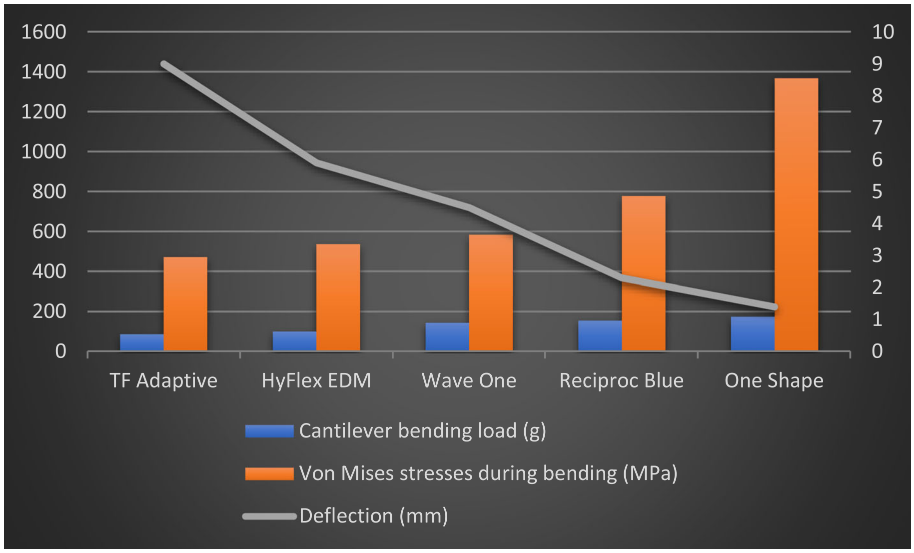

Fig. 10 Bar chart showing results of cantilever bending test, von Mises stress, and bending deflection during bending among the different endodontic instruments

Abbreviations
FEA: Finite element analysis; NiTi: Nickel-titanium; CT: Computerized tomography; 3D: Three-dimensional; 2D: Two-dimensional; CAD: Computer aided design; ANOVA: A one-way analysis of variance

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Authors' contributions
A. G. Ismail, M. Galal, M. H. Zaazou, T. M. Hamdy, and R. M. Abdelraouf contributed to the conception and design of the study, experimental work, interpretation of the analyzed data, and writing the manuscript and revised and reviewed the draft manuscript. All authors have read and approved the manuscript.

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Competing interests
The authors declare that they have no competing interests.

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