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Mechanical behavior of three nickel-titanium rotary files: A comparison of numerical simulation with bending and torsion tests

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ABSTRACT

Aim: To assess the flexibility and torsional stiffness of three nickel-titanium rotary instruments by finite element analysis and compare the numerical results with the experiment.
Methodology: Mtwo (VDW, Munich, Germany) and RaCe (FKG Dentaire, La-Chaux-de-Fonds, Switzerland) size 25, .06 taper (0.25-mm tip diameter, 0.06% conicity) and PTU F1 (Dentsply Maillefer, Ballaigues, Switzerland) instruments were selected for this study. Experimental tests to assess the flexibility and torsional stiffness of the files were performed according to specification ISO 3630-1. Geometric models for finite element analysis were obtained by micro-CT scanning. Boundary conditions for the numerical analysis were based on the specification ISO 3630-1.
Results: A good agreement between the simulation and the experiment moment–displacement curves was found for the three types of instruments studied. RaCe exhibited the highest flexibility and PTU presented the highest torsional stiffness. Maximum values of von Mises stress were found for the PTU F1 file (1185 MPa) under bending, whereas the values of von Mises stress for the three instruments were quite similar under torsion. The stress patterns proved to be different in Mtwo under bending, according to the displacement orientation.
Conclusions: The favorable agreement found between simulation and experiment for the three types of instruments studied confirmed the potential of the numerical method to assess the mechanical behavior of endodontic instruments. Thus, a methodology is established to predict the failure of the instruments under bending and torsion.

1. Introduction

Endodontic treatment is a clinical intervention that aims to cure infections in the pulp of the tooth, the soft tissue inside the root canal. This treatment includes a step of shaping the root canal by means of an endodontic instrument, made of stainless steel or nickel-titanium (NiTi) alloy. Rotary NiTi endodontic instruments present several advantages when compared to stainless steel instruments, such as higher flexibility, producing less canal aberrations and requiring lower procedural time [1,2]. These advantages are associated with the NiTi alloys' superelasticity (or pseudoelasticity), a nonlinear elastic behavior that allows the material to undergo high deformation without plastic residual-strain after stress removal. This behavior is due to a reversible solid-state transformation from the parent phase austenite to a new crystallographic structure called martensite [3,4].

Despite their advantages, fracture of NiTi instruments remains a concern in clinical practices. The failure of these instruments may occur by torsional overloading or flexural fatigue during the root canal preparation. Torsional failure occurs when the tip of the instrument is locked in the canal while the shaft continues to rotate [5,6]. Flexural-fatigue failure takes place when the instrument rotates inside a curved canal and is subjected to an excessive number of tensile-compressive strain cycles in the region of maximum canal curvature [6–8]. The stresses generated during flexural loading are directly associated to the fatigue life of the material. Thus, bending and torsion are essential conditions to evaluate the mechanical behavior of the endodontic instruments.

The mechanical responses of endodontic instruments are related to several factors such as pitch length, taper or conicity, alloy chemical composition and thermomechanical processing [9–11]. However, there is a strong relationship between the cross-sectional design and the stress distribution pattern of an instrument subjected to bending or torsion [12–14]. Furthermore, depending on the cross-sectional

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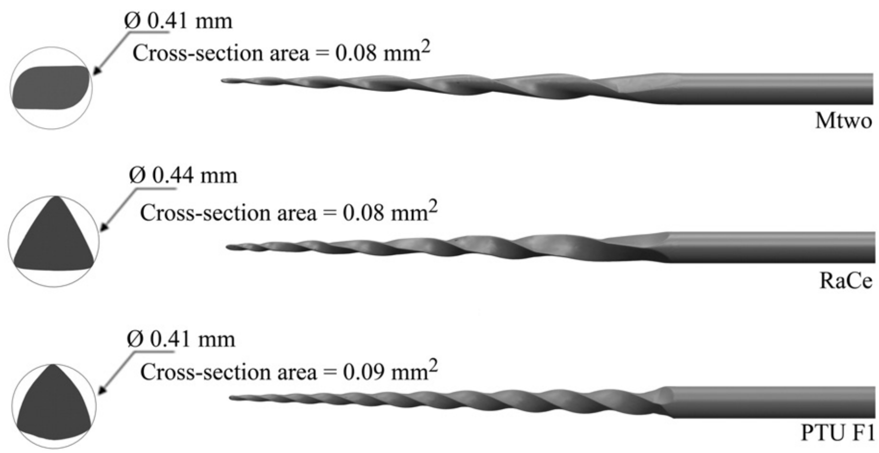

Fig. 1. Endodontic instruments: 3D geometrical models and respective cross-sections at 3 mm from the tip. The models were obtained by micro-CT scanning.

geometry, the bending orientation can have an important influence on the mechanical responses of the instrument [15].

Flexibility and torsional stiffness are mainly studied by means of laboratory tests [6,7,10]. Nevertheless, these tests are fastidious and expensive, which makes the finite element analysis (FEA) an efficient alternative to study the mechanical behavior of endodontic instruments. Another advantage of FEA is the possibility of assessing aspects of the mechanical behavior of the instruments, such as stress distribution, which are difficult to obtain in laboratory tests. Although some studies have been performed on the influence of instrument geometry on their flexibility and torsional stiffness by using FEA [15–20], to the extent of our knowledge, no direct comparison between numerical and experimental results has been performed. Furthermore, most of the published reports [16,19,20] do not stipulate criteria for the determination of the boundary conditions, such as the specification ISO 3630-1 [21].

The aim of this study was thus to evaluate the mechanical behavior of three commercially available instruments using FEA and compare the numerical results with those obtained by standard mechanical tests to assess the reliability of the FEA models. The mechanical behavior was characterized by flexibility (and its reciprocal flexural stiffness) and torsional stiffness. The influence of the cross-sectional design on the stress distribution and the importance of the bending orientation were also investigated.

2. Materials and methods

Three types of NiTi rotary instruments were selected for this study: size 25, .06 taper (0.25-mm tip diameter, 0.06% conicity) Mtwo (VDW, Munich, Germany), RaCe (FKG Dentaire, La-Chaux-de-Fonds, Switzerland) and PTU F1 (Dentsply Maillefer, Ballaigues, Switzerland). In the following, the experimental tests and the finite element models are described.

Table 1
Parameters used to describe the constitutive model of the superelastic NiTi.

Parameter	Description	Value
E_A	Austenite elasticity	42,530 MPa
ν_A	Austenite Poisson's ratio	0.33
E_M	Martensite elasticity	12,828 MPa
ν_M	Martensite Poisson's ratio	0.33
ε^L	Transformation strain	10%
$(\delta\sigma/\delta T)_L$	$(\delta\sigma/\delta T)$ loading	6.7
σ_L^S	Start of transformation loading	492 MPa
σ_L^E	End of transformation loading	630 MPa
T_0	Reference temperature	22 °C
$(\delta\sigma/\delta T)_U$	$(\delta\sigma/\delta T)$ unloading	6.7
σ_U^S	Start of transformation unloading	192 MPa
σ_U^E	End of transformation unloading	97 MPa
σ_{ME}^E	End of martensitic elastic regime	1200 MPa

2.1. Experimental tests

One group of instruments ($n = 12$ of each type) was tested for bending resistance according to specification ISO 3630-1, using the apparatus described by Viana et al., 2013 [22]. The instruments were fixed at 3 mm from the tip and then bent 45° with respect to their long axis while the bending force was recorded by a load cell. Values of bending moment were obtained by multiplying the registered bending force by the distance between the point at which the force was applied and the fixed tip of the instrument.

Another group ($n = 12$ of each type) was tested in torsion until fracture, based on ISO 3630-1 specification, using a torsion machine (AN8050, Analogica, Belo Horizonte, MG, Brazil) described in detail else where [23]. The rotation speed was set clockwise to 2 rpm. For this test, the instruments were also fixed at 3 mm from the tip, while the shaft's end was clamped and connected to a reversible geared motor. A specifically designed computer program provided a continuous recording of torque and angular deflection.

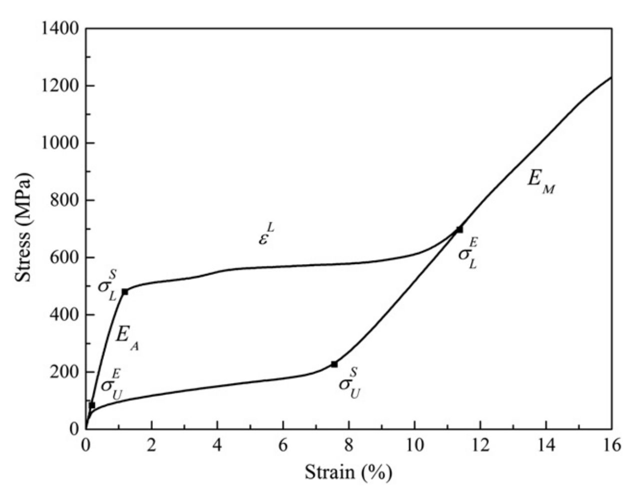

Fig. 2. Average stress–strain curve of a superelastic NiTi alloy used in the constitutive model.