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CYCLIC AND TORSIONAL FATIGUE RESISTANCE OF THERMALLY TREATED ROTARY NiTi INSTRUMENTS WITH DIFFERENT DESIGNS

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ABSTRACT

Aims: The aim was to evaluate the cyclic and torsional fatigue resistance among thermally treated NiTi rotary instruments with different design features.

Materials and methods: Sixty instruments of three systems were used (n=20): TruNatomy 26.04 (TN 26.04), BassiLogic 25.05 (BL 25.05), and Flat File 25.04 (FF 25.04). The cyclic fatigue test (n=10) was performed to evaluate the time to fracture (s) and the number of cycles until failure (NCF). The torsion test was performed to evaluate the torque (N.cm) and maximum angular deflection until fracture (n=10). The fracture surface of each fragment was examined under a scanning electron microscope. The data were analyzed by Tukey's test ($p<0.05$).

Results: BL 25.05 and FF 25.04 instruments had a higher number of cycles and time to fracture compared with TN 26.04 ($p<0.05$). TN 26.04 instruments showed lower torque to fracture.

Conclusions: Based on the proposed objectives and the methodology used, TruNatomy 26.04 instruments present lower resistance to cyclic fatigue and torsional fatigue when compared to BassiLogic 25.05 and Flat File 25.04 instruments.

KEYWORDS: Torsional fatigue. Cyclic fatigue. Rotatory Instruments.

INTRODUCTION

Nickel-Titanium (NiTi) rotary instruments have been widely used for the preparation of curved root canals thanks to their high flexibility, providing safety with low risk of instrumentation errors[1,2]. However, an unexpected fracture can occur as a result of cyclic or torsional fatigue[3].

Cyclic fatigue occurs when the instruments rotate in a curved root canal and are subjected to tensile and compressive forces at their maximum point of flexion, which can lead to rupture of the metallic alloy[3]. Torsional fatigue occurs when the tip of the instrument is trapped in the dentinal walls and the instrument continues to rotate, which can lead to plastic deformation and, eventually, to instrument breakage[4].

Over the years, manufacturers have made several changes to the designs, manufacturing process, kinematics, and heat treatments of NiTi alloys with the objective of optimizing the mechanical properties of the instruments[1,2,6]. Heat treatment of NiTi provides a better arrangement of the crystalline structure of the metal alloy, increasing R-phase or martensitic-phase transformation in clinical conditions[1], resulting in greater flexibility and resistance to cyclic fatigue when compared to conventional NiTi[1,5].

Recently, the concept of minimally invasive endodontics has been gaining more attention with the aim of reducing tooth structure loss[7]. Therefore, instruments with smaller tapers and different design have been proposed to reduce pericervical dentin removal[8,9], thus reducing the risk of tooth fracture[9,10].

The TruNatomy rotary system (Dentsply Maillefer, Baillagueis, Switzerland) is made of a heat-treated NiTi alloy and consists of five instruments, which have a cross-sectional design of a decentralized parallelogram[11]. In addition, the instruments have a taper of 0.03 to 0.04 mm/mm, providing a more conservative preparation with less pericervical dentin removal[12]. The combination of design and heat treatment provides adequate mechanical resistance, cutting efficiency, and debris removal during root canal preparation[13].

Recently, two new rotary systems have been launched on the market. The BassiLogic rotary system (BassiEndo, Belo Horizonte, Minas Gerais, Brazil) is composed of instruments with different diameters and 0.05 mm/mm taper, with an italic S cross-section and made with NiTi controlled memory alloy. BassiLogic instruments have a fixed taper of 0.05 mm/mm up to the portion where the active blade reaches 1.0 mm in diameter, and from that point onwards the instrument becomes cylindrical. The instrument has been designed to enable less removal of cervical dentin and greater flexibility by reducing metal volume.

The Flat File rotary system (MKLife, Porto Alegre, Rio Grande do Sul, Brazil) uses the design concept proposed by Gambarini et al.[14] (2019), who demonstrated that a modified S section (Flat) provided greater resistance to cyclic fatigue when compared to conventional italic S. The Flat File system consists of instruments with a taper of 0.04 mm/mm, NiTi alloy with Gold heat treatment, surface polishing, a flat S cross section and instruments with tip diameter #20, #25 and #35. There are no studies in the literature on the mechanical properties of these new instrument systems.

The evaluation of the mechanical properties of NiTi rotatory instruments can improve clinician's understanding of the instrumentation system and help them make better choices when confronted with different anatomical challenges. Therefore, it is essential that the new systems be carefully evaluated by laboratory tests to determine mechanical fatigue and the shaping ability of root canals. The aim of this study was to evaluate the cyclic and torsional fatigue strength of BassiLogic 25.05, Flat File 25.04, and TruNatomy 26.04 instruments. The null hypotheses state that:

1. There is no difference in cyclic fatigue strength between instruments;
2. There is no difference in torsional resistance between the instruments.

MATERIALS AND METHODS

Sample size calculation

G*Power v3.1 for Mac (Heinrich Heine, Universität Düsseldorf, Dusseldorf, Bundesland, Germany) was used for sample calculation, and the Wilcoxon-Mann-Whitney test was selected from the T test family. Data from one study[15] were used and the effect size of the present study was established (=1.80). An alpha type error of 0.05, a beta power of 0.80, and an N2/N1 ratio of 1 were also established. A total of 10 instruments per group were indicated as the optimal size needed for significant differences.

Twenty 25-mm-long instruments were selected per group (TruNatomy 26.04 (TN 26.04), BassiLogic 25.05 (BL 25.05), and Flat File 25.04 (FF 25.04)) and subjected to cyclic fatigue and torsional strength tests (n=10). Prior to the mechanical tests, all instruments were inspected on a stereomicroscope (Stemi 2000C; Carls Zeiss, Jena, Germany) at 16x magnification to evaluate possible defects or deformities; none were discarded.

Cyclic fatigue test

The cyclic fatigue test was performed in a device that could simulate the curvature of an artificial stainless steel canal with 60º of curvature and 5 mm of radius, as previously described by Alcalde et al.[15] (2018). The curvature of the canal was adjusted by a guide cylinder (5-mm radius) and by an external arch with a 1-mm-deep groove, which served as a guide for the instruments and kept them in the curvature, rotating freely. The cyclic fatigue tests were performed at body temperature (35°±1°C) using a water bath, as previously reported by other authors[16].

All instruments were activated using the same rotational speed and torque to ensure similar conditions for the instruments, reducing other variables. The instruments were activated with 500 rotations per minute (rpm) and 1.5 N.cm of torque. Time to fracture was measured using a digital stopwatch and confirmed by filming, which was performed concomitantly with the test. After the time-to-fracture measurement, the number of cycles was calculated using the following formula: time to fracture (in seconds) X speed (rpm) / per 60 (NCF).

Torsional fatigue test

The torsion test was performed following ISO 3630-1 standard[15]. The mandrel was removed from all instruments to allow gripping them onto the torsion test machine. The first 3 mm of the instrument tip was mounted on a screw-on chuck coupled to a torque cell and the other end was connected to a reversible gear motor.

To start the torsion test, the reversible motor was activated by software specifically designed for this machine (Analógica, Belo Horizonte, Minas Gerais, Brazil), which rotated the instrument clockwise at a speed of 2 rpm. Concomitantly with motor rotation, the software provided the torque values (N.cm) and the angulation (º) performed by the motor up to instrument breakage, when the equipment automatically came to a halt. The obtained data were exported to an Excel spreadsheet and the maximum torque and angulation at the time of instrument breakage were recorded.

SEM analysis of the fractured surface

Topographic characteristics of the fractured surfaces of all fragments were examined in a high-vacuum scanning electron microscope (SEM) (JSM –T220A, Jeol, Tokyo, Japan). The instruments previously subjected to cyclic fatigue test were evaluated at 150x and 350x magnification, while those instruments subjected to the torsional fatigue test were assessed at 200x and 500x magnification.

Statistical analysis

Data were evaluated by one-way analysis of variance (ANOVA) to compare the outcomes between the groups. Tukey's post-hoc test was used for multiple comparisons. The significance level was set at p = 5% (GraphPad Prism, San Diego, USA).

RESULTS

The mean and standard deviations of cyclic fatigue strength, maximum torque load, and rotation angle to fracture for each instrument are shown in **Table 1**. BL 25.05 and FF 25.04 instruments showed longer time to fracture and NCF as compared to TN instruments 26.04 ($p<0.05$), with no difference between them ($p>0.05$). Regarding torque, TN 26.04 presented lower fracture torque when compared to BL 25.05 and Flat File 25.04 ($p<0.05$), and there was no statistically significant difference between BL and FF ($p>0.05$). In the angular deflection analysis, there was no statistically significant difference between FF 25.04 and TN 26.04 ($p>0.05$) and both were smaller when compared to BL 25.05 ($p<0.05$).

Scanning electron microscopy of the fracture surface showed similar and typical features of cyclic fatigue and torsional failure for the two brands. Crack initiation point indicative of ductile failure during the last stage of rapid crack propagation for cyclic fatigue fractures are shown in **Figure 1** and concentric abrasion marks at the center of rotation for torsional failure are shown in **Figure 2**.

DISCUSSION

Currently, several NiTi rotary instruments with different design and thermal treatments were introduced in the market to ensure safe root canal preparation in the curved and constricted canals. Also, some authors have been proposed a rational removal of cervical dentine and an increase in the apical diameter to ensure a balance between antimicrobial efficacy and prevention of dental fractures[17]. Therefore, new NiTi rotary instruments have been developed for this purpose[18,19].

The evaluation of the cyclic and torsional fatigue strength of NiTi rotatory instruments has the objective of simulating a high mechanical stress, similar to what occurred during the preparation of curved or constricted canals, allowing the determination of the mechanical behavior of the instruments in view of different anatomical challenges. By doing that, the clinician can understand which instrument may have a greater or lesser tendency to fracture[2,3]. The aim of this study was to compare the cyclic and torsional fatigue properties between three rotatory instruments: Flat File 25.04, BassiLogic 25.05, and TruNatomy 26.04. The null hypotheses were that there would be no difference in cyclic and torsional fatigue strength between the systems.

Although some previous studies have evaluated the mechanical properties of instrument 26.04 of the TruNatomy system[13,20,21], there are no

Table 1. Means and standard deviations (in parentheses) of time, number of cycles, torque, and angular deflection results from cyclic and torsional fatigue tests.

Instrument	Cyclic fatigue		Torsional fatigue	
	Time (s) Mean (SD)	Cycles (NCF) Mean (SD)	Torque(N.cm) Mean (SD)	Angle of rotation(º) Mean (SD)
BassiLogic 25.05	195,7 (23,86)[a]	1624,0 (198,00)[a]	0,9 (0,15)[a]	820,9 (117,30)[a]
Flat File 25.04	200,7 (84,16) [a]	1665,0 (297,3)[a]	1,1 (0,14)[a]	578,1 (73,71)[b]
TruNatomy 26.04	79,0 (7,24)[b]	655,7 (60,11)[b]	0,6 (0,06)[b]	588,6 (32,93)[b]

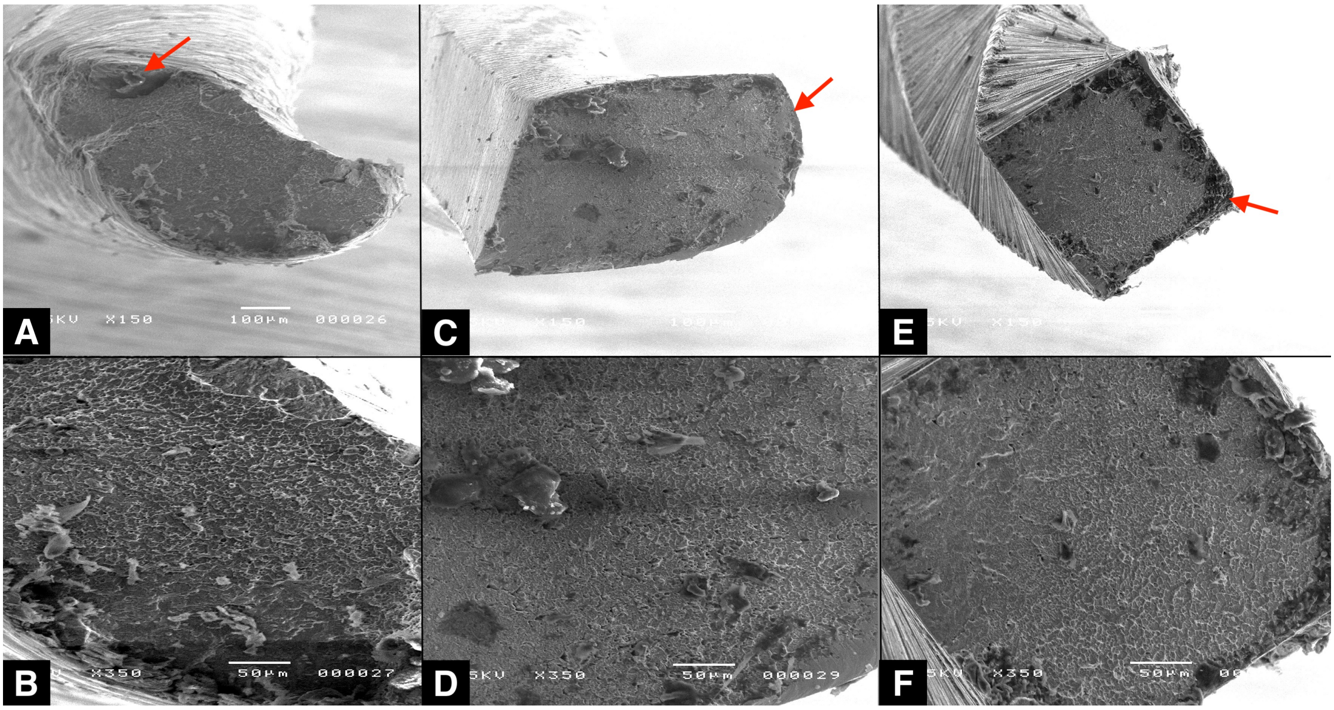

Figure 1. High-vacuum scanning electron microscope (SEM) images of fractured surfaces of separate fragments of BassiLogic (**A, B**), Flat File (**C, D**), and TruNatomy (**E, F**) instruments after cyclic fatigue testing, with arrows indicating the origin of crack initiation at 150x magnification in the upper row and at 350x in the lower row. The surface pattern shows undulations, and the cones are seen in the same fracture plane.

data to date on the mechanical properties of BassiLogic and Flat File systems; therefore, it is appropriate to evaluate it and compare it with a reference system in the world market. The results of the cyclic and torsional fatigue tests showed a significant difference between the evaluated instruments ($p<0.05$). Therefore, the null hypotheses were rejected.

There is an extensive discussion in the endodontic literature about the use of a dynamic cyclic fatigue test, as it seems to be a more sensitive method and can assess variables other than the type of instrument[22]. The dynamic fatigue test produces less localized mechanical stresses, increasing the time and number of cycles to fatigue[22,23]. In addition, depending on the design of the tube or artificial groove, torsional stresses can be created, which can compromise the identification of the type of fatigue that occurred[24].

Therefore, as previously reported[16,22,23], the static cyclic fatigue methodology in a controlled laboratory environment was used in this study, seeking to reduce some biases, increasing the validity and reproducibility of the method, which allows a better understanding of the mechanical behavior of the instruments[23]. In this method, the instruments are mounted on a stabilized handpiece and rotate freely in an artificial canal with pre-defined characteristics and under specific conditions up to instrument fracture[23], providing better information on the impact of different instrument design characteristics or NiTi alloy[22,23].

The results of the cyclic fatigue test showed that BL 25.05 and FF 25.04 instruments presented longer time to fracture and NCF as compared to TN 26.04 instruments ($p<0.05$). Previous studies showed that the TN 26.04 system showed greater strength to cyclic fatigue than did the other instruments (ProTaper Next 25.06[21], FlexMaster 20.04[13], VortexBlue 25.04[22], and RaCe 25.04[21]). However, Uslu et al.[20] (2020) showed that VDW Rotate 25.04 and Hyflex CM 25.04 presented greater strength to cyclic fatigue when compared to TN 26.04. On the other hand, there are no data on BL 25.05 and FF 25.04.

The design and centrality of the cross section, taper, core diameter, and distance between the blades can influence the bending moment and, consequently, the strength to cyclic fatigue, as the volume of metal at the maximum bending point can influence flexibility[1,2,22,24]. To understand the cyclic fatigue strength of rotatory instruments, it is necessary to evaluate the flexural section modulus by the following formula: $Z = I/y$ (where I = moment of inertia; y = distance from the neutral line (surface that separates the compressed zone from the tension) to any point on the instrument, the impact being explained by the distance from the neutral line at the center of

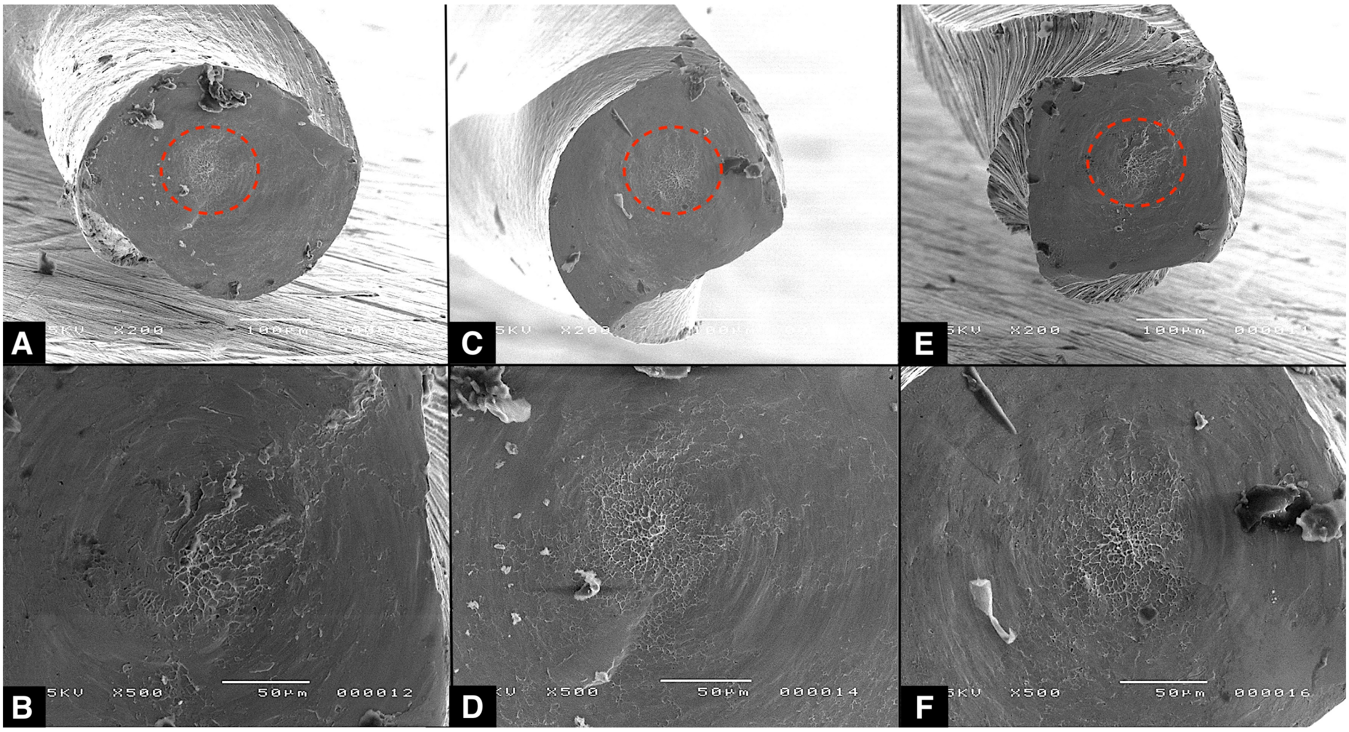

Figure 2. High-vacuum scanning electron microscope (SEM) images of fractured surfaces of separate fragments of BassiLogic (**A, B**), Flat File (**C, D**), and TruNatomy (**E, F**) instruments after the torsional fatigue test, with circular case indicating the concentric abrasion mark at 200x magnification in the upper row and at 500x in the lower row. Skewed undulations near the center of rotation are typical characteristics of torsional faults.

the instrument to the surface of the cross-section and its geometry[25]. In the case of cross-sections that are asymmetrical, TruNatomy and Flat File, the mechanical strength and force dissipation change according to their design, which is more significant than the taper[26]. However, the variables between the instruments tested are diverse (taper, core, cross-section, etc.), making the comparison and the exact justification that explains our results challenging. Therefore, it becomes clear that the design differences between the instruments significantly impacted our results[1,5,22].

Another fundamental point to consider for cyclic fatigue strength tests are the heat treatments of the NiTi alloy[1,5,15]. It has been previously demonstrated that the use of body temperature during mechanical testing better mimics a real clinical condition[16,27]. However, the type of heat treatment directly affects the flexibility of NiTi instruments, as they provide a greater presence of R-phase and/or martensitic phase, modifying the energy required for the formation and/or propagation of cracks in the instrument blade[5]. Furthermore, the final austenite temperature is different between heat treatments, which may have significantly affected the results of this study.

The BassiLogic instrument features an alloy with memory control (CM); the Flat File instrument permits Gold heat treatment; and TruNatomy allows a special heat treatment not specified by the manufacturer. Gold heat-treated instruments have a final austenite temperature of approximately 50°C[27], indicating that these instruments also contain martensite or R phase under clinical conditions[5], proving that the transformation temperature of each instrument influences in its crystallographic arrangement[27].

The BassiLogic instrument features an alloy with memory control (CM); the Flat File instrument permits Gold heat treatment; and TruNatomy allows a special heat treatment not specified by the manufacturer, which probably favor different percentage of martensite or R phase, which probably justify our results. Previous studies of Differential Scanning Calorimetry (DSC) analysis reported that the austenite finish (Af) temperature of the NiTi manufactured by CM and Gold technology is around 47-60°C and 50°C, respectively[5]. In addition, Silva et al.[29] demonstrated that TruNatomy instruments present a Af temperature around 29.2°C. Therefore, the TruNatomy instruments probably suffered a crystallographic rearrangement leading to a higher percentage of austenitic phase compared with the other instruments, justifying the lowest cyclic fatigue resistance. Future studies should be conduct using DSC analysis to confirm the above mentioned factor among the instruments evaluated in this study.

The torsional fatigue test used in this study has been published previously[4,15] and performed according to the criteria described in ISO 3630-1 standard. This test aims to generate a high torsional stress at 3 mm from the tip of the instruments, allowing the assessment of the maximum torque and angular deflection for the fracture of the instruments and their probable susceptibility to fracture in calcified canals[15]. The properties of the instruments were evaluated in the initial 3 mm, as this is the area of greatest susceptibility to fracture during root canal preparation[15].

The results of the torsional test showed that BL 25.05 had greater angular deflection than that of TN 26.04 and FF 25.04 ($p<0.05$). Regarding torque, TN 26.04 presented the lowest torque for fracture as compared to BL 25.05 and FF 25.04 ($p<0.05$). The differences are closely related to the same factors mentioned for cyclic fatigue strength. The torsional properties of rotatory instruments are dependent on the NiTi alloy, taper, cross-section, and moment of inertia[25]. There is a tendency for more cyclically resistant instruments to have greater angular deflection and less touch, as they are more flexible[15,30], thus corroborating the results of this present study.

Regarding the SEM analysis, typical characteristics of cyclic and torsional fatigue were observed for all tested instruments: after the cyclic fatigue test, all evaluated instruments showed areas of crack initiation and overload zones, with numerous undulations spread across the fractured surface; after the torsion test, the fragments showed concentric marks of abrasion and undulations at the center of rotation[15,22].

Although these are laboratory data, they are of great importance to the clinician, serving as a reference for which anatomical features each instrument can be safely used. The greater resistance to cyclic and torsional fatigue of BassiLogic and Flat File may be an indication to choose these instruments in clinical situations of curved and atretic canals more safely when compared to TruNatomy instruments. Nevertheless, future clinical studies are needed to confirm this hypothesis.

CONCLUSION

Despite the limitations of this study, we can conclude that the design characteristics and heat treatments of the tested instruments demonstrated a significant impact on cyclic and torsional fatigue tests. Bassi Logic 25.05 and Flat File instruments presented highest cyclic fatigue resistance and torsional strength to fracture than truNatomy 26.04 instruments. However, truNatomy 26.04 and flat file presented similar values regarding maximum angular deflection.

ACKNOWLEDGEMENTS

The authors would like to thank the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001 and the Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP- 2018/2323-6) for the financial support.

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