UNIVERSIDADE DE SÃO PAULO
FACULDADE DE ODONTOLOGIA DE BAURU

JUSSARO ALVES DUQUE

Analysis of the quality of root canal preparation and retreatment using different instruments associated or not with different irrigant agitation protocols

Análise da qualidade do preparo e do retratamento de diferentes instrumentos associados ou não a diferentes protocolos de agitação do irrigante

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Orientador: Prof. Dr. Clovis Monteiro Bramante

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“Por vezes sentimos que aquilo que fazemos não
é senão uma gota de água no mar. Mas o mar
seria menor se lhe faltasse uma gota”.
(Madre Teresa de Calcuta)

RESUMO

Análise da qualidade do preparo e do retratamento de diferentes instrumentos associados ou não a diferentes protocolos de agitação do irrigante

Introdução: Os objetivos foram: artigos I e II - avaliar a qualidade do preparo, em canais curvos, de sistemas reciprocantes e a fadiga cíclica, de instrumentos novos e usados; artigo III - avaliar a qualidade do preparo, em canais curvos, de sistemas rotatórios e avaliar a resistência a fadiga torsional e cíclica dos instrumentos de glidePath e de acabamento final, respectivamente, tanto novos como usados; artigo IV - avaliar a qualidade no retratamento de canais curvos e a fadiga cíclica, de instrumentos novos e usados, de diferentes sistemas mecanizados; artigo V - avaliar a eficiência na remoção de material obturador remanescente com diferentes protocolos de irrigação. **Metodologia:** artigos I, II e III - foram utilizados os seguintes sistemas para instrumentar: Reciproc Blue 25.08 e 40.06; WaveOne Gold 25.07 e 35.06; ProDesignR 25.06 e 35.05; BT-Race 10.06, 35.00 e 35.04; Sequence Rotary File 15.04, 25.06 e 35.04; ProDesign Logic 25.01, 25.06 e 35.05. Cada sistema foi utilizado em 3 dentes. Artigo I - foi avaliado o transporte, volume e áreas não tocadas pelos instrumentos reciprocantes. Artigo II - fadiga cíclica dos instrumentos reciprocantes novos e usados. Artigo III - foi avaliado o transporte, centralização, volume, fadiga torsional e fadiga cíclica dos sistemas rotatórios. Artigo IV - os canais foram obturados e divididos de acordo com os sistemas de retratamento: Reciproc 25.08 e 40.06, Reciproc Blue 25.08 e 40.06, Pro-R 25.08 e 40.06 e ProDesign LogicRT 25.08 e 40.05. Foi utilizado um instrumento por dente. Avaliou-se o material obturador remanescente, o tempo necessário para o instrumento 25 atingir o comprimento de trabalho e a fadiga cíclica. Artigo V – após o retratamento, foram aplicados os seguintes protocolos de irrigação: Irrigação ultrassônica contínua com Irrisafe, Irrigação ultrassônica contínua com NiTiSonic, Irrigação ultrassônica passiva com Irrisafe, Irrigação ultrassônica passiva com NiTiSonic, Eddy e XP-endoFinisherR. Avaliou-se o volume de material obturador removido. **Resultados:** I – WaveOne Gold apresentou maior aumento no volume e não houve diferença no transporte e áreas não-tocadas. II - ProdesignR apresentou maior resistência a fadiga cíclica. III - não houve diferença no transporte, centralização e volume. Fadiga torsional, Sequence Rotary File e ProDesign Logic tiveram melhores resultados de torque e deflexão angular, respectivamente; na fadiga cíclica ProDesign Logic foi mais resistente. IV – ProDesign LogicRT removeu mais e mais rápido o material obturador. Na fadiga cíclica, Reciproc Blue e ProDesign LogicRT foram mais resistentes. V - Não houve diferenças entres os protocolos de irrigação. **Conclusões:** I - todos os sistemas

apresentaram boa qualidade no preparo do canal radicular. II - ProDesignR apresentou maior resistência a fadiga cíclica. III – todos os sitemas apresentaram boa qualidade no preparo, Sequence Rotary File apresentou maior torque e ProDesign Logic maior deflexão angular e resitência cíclica. IV – ProDesign LogicRT removeu mais material obturador remanescente e foi mais rápido. Reciproc Blue e ProDesign LogicRT tiveram maior resistência cíclica. IV – Nenhum protocolo removeu completamente o material obturador e não houve diferença entre eles.

Palavras-chave: Endodontia. NiTi. Fadiga cíclica. Fadiga torsional. Retratamento. Irrigação.

ABSTRACT

Analysis of the quality of root canal preparation and retreatment using different instruments associated or not with different irrigant agitation protocols

Introduction: The objectives were: articles I and II - to evaluate the quality of preparation in curved canals of reciprocating systems and cyclic fatigue of new and used instruments; article III - to evaluate the quality of the preparation, in curved canals, of rotary systems and resistance to torsional and cyclic fatigue ,of the new and used glidePath and final instruments, respectively; article IV - to evaluate the quality in the retreatment of curved canals with different systems and the cyclical fatigue, of new and used instruments; article V - evaluate the efficiency in the removal of filling material with different irrigation protocols. **Methodology:** articles I, II and III - the following instrumentation systems were used: Reciproc Blue 25.08 and 40.06; WaveOne Gold 25.07 and 35.06; ProDesignR 25.06 and 35.05; BT-Race 10.06, 35.00 and 35.04; Sequence Rotary File 15.04, 25.06 and 35.04; ProDesign Logic 25.01, 25.06, and 35.05. Each system was used on 3 teeth. Article I - the transportation, volume and untouched areas were evaluated. Article II - cyclical fatigue of new and used reciprocating instruments were evaluated. Article III - transport, centralization, volume, torsional fatigue and cyclic fatigue of the rotary systems were evaluated. Article IV - the canals were filled and divided according to the retreatment systems: Reciproc 25.08 and 40.06, Reciproc Blue 25.08 and 40.06, Pro-R 25.08 and 40.06 and ProDesign LogicRT 25.08 and 40.05. One instrument was used per tooth. The remaining filling material was measured, the working time required for the instrument 25 to reach working length and cyclic fatigue. Article V - the following irrigation protocols were applied: Continuous Ultrasonic Irrigation with Irrisafe, Continuous Ultrasonic Irrigation with NiTiSonic, Passive Ultrasonic Irrigation with Irrisafe, Passive Ultrasonic Irrigation with NiTiSonic, Eddy and XP-endoFinisherR. The volume of filling material removal was evaluated. **Results:** I – WaveOne Gold presented greater increase in volume and there was no difference in transport and untouched areas. II – ProdesignR presented greater resistance to cyclic fatigue. III - there was no difference in transportation, centralization and volume. Torsional fatigue, Sequence Rotary File and ProDesign Logic showed higher values torque and angular deflection, respectively; in cyclic fatigue ProDesign Logic was more resistant. IV – ProDesign LogicRT removed more and faster filling material. In cyclic fatigue, Reciproc Blue and ProDesign LogicRT were more resistant. V - There were no differences among the irrigation protocols. **Conclusions:** I - all the systems presented good quality in the preparation of the root canal. II - ProDesignR

presented greater resistance to cyclic fatigue. III - all the systems presented good quality in the preparation, Sequence Rotary File presented higher torque and ProDesign Logic greater angular deflection and cyclic resistance. IV – ProDesign LogicRT removed more remaining filling material and was faster. Reciproc Blue and ProDesign LogicRT had greater cyclic resistance. IV - No protocol completely removed the filling material and there was no difference among them.

Key words: Endodontics. NiTi. Cyclic fatigue. Torsional fatigue. Retreatment. Irrigation.

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1 Introduction

1 INTRODUCTION

The chemomechanical preparation is one of the important steps of endodontic treatment, determining a suitable conformation of the root canal to receive the filling material. The challenge of performing a correct shaping of the root canal becomes greater when it presents some type of curvature (WU et al., 2015; LIU et al., 2016).

Therefore, it is fundamental that the instrument used to shape be able to maintain the original trajectory of the root canal without causing transportation, rectification of the curvature and even perforations (SANT'ANNA JÚNIOR et al., 2014; LIU et al., 2016). In order to reduce procedural errors in this step, mechanized rotary and reciprocating systems were introduced using nickel-titanium (NiTi) alloys with different types of thermal treatment, in order to perform especially the shaping of curved canals where the stainless steel instruments have a great limitation (HWANG et al., 2014; FRUCHI et al., 2014).

Among the various systems available on the market, Reciproc (VDW, Munich, Germany) is one of the most widely used instruments described in the literature. It is used in alternating motion (reciprocating) where a movement of 150° counterclockwise (cut direction) and 30° clockwise (relief) is performed (KIM et al., 2012; HWANG et al., 2014). This instrument is fabricated with an NiTi M-Wire alloy and has been used for both canal shaping and retreatment (KAŞIKÇI BILGI et al., 2017; DE-DEUS et al., 2019a). Recently, Reciproc Blue was introduced on the market in which the NiTi alloy undergoes a new heat treatment where the molecular structure of the NiTi is modified giving greater flexibility and strength, according to the manufacturer. This process gives the instrument the blue color which justifies its name. These new instruments have the same design and size as previous ones, which are: 25.08 (Primary), 40.06 (Medium) and 50.05 (Large). Like its predecessor, studies have demonstrated its efficiency in canal preparation and endodontic retreatment (DE-DEUS et al., 2019a; BORGES et al., 2019).

Another well-known and studied instrument is WaveOne (Dentsply Maillefer, Ballaigues, Switzerland). Like Reciproc (VDW), it is used in reciprocating motion, but the angles used are 170° counterclockwise (cut-off direction) and 50° clockwise (relief). It is also manufactured with the NiTi alloy M-Wire (HWANG et al., 2014; DA ROSA et al., 2015) that underwent a heat treatment process producing instruments with greater flexibility and resistance to fracture (ADIGÜZEL et al., 2017). This treatment results in a golden color that gave rise to the name of the instrument. WaveOne Gold are manufactured in 4 different sizes that are: 20.07 (Small), 25.07 (Primary), 35.06 (Medium) and 45.05 (Large).

A few years ago, the ProDesign R (reciprocating) and ProDesign Logic (rotary) systems (Easy Dental Equipments, Belo Horizonte, MG, Brazil) were also introduced to the market. ProDesign R is used in alternating rotation, with 300° counterclockwise (cut-off direction) and 30° clockwise (relief). The ProDesign Logic indicated for shaping and ProDesign Logic RT for retreatment are used in continuous rotation at a speed of 900 RPM and 4 N of torque, according to the manufacturer's instructions. These instruments are manufactured with a different hybrid design and NiTi alloy with control memory (CM) technology, which gives the instruments great flexibility and resistance to cyclic fatigue, thus having greater safety (ALCALDE et al., 2018a; ALCALDE et al., 2018b).

Another rotary instrumentation system is the BT-Race (FKG, La Chaux-de-Fonds, Switzerland). It consists of five instruments, 10.06, 30.00, 35.04, 40.04 and 50.04 and is used in continuous rotation at a speed of 800 RPM and 1.5 Ncm of torque. The manufacturer claims that one of the great advantages of this system is the low torque used which minimizes the risk of fracture of the instrument. These instruments are manufactured with conventional NiTi alloys that undergo an electropolishing process (DA SILVA LIMOEIRO et al., 2016).

Recently, the Brazilian company MK Life has introduced new mechanized systems, both reciprocating and rotating, for shaping and retreatment. Within these systems, the Sequence Rotary File (MKLife, Porto Alegre, RS, Brazil) is composed of 4 instruments (15.04, 20.06, 25.06 and 35.04) manufactured in NiTi with blue heat treatment and the reciprocating system for retreatment called Pro-R (MKLife) which has an M-Wire thermal treatment in its alloy.

In addition to the need for mechanized systems to be able to properly shape the canal, it is also important that the instruments have good mechanical properties such as good resistance to cyclic fatigue, especially in curved canals (DUQUE et al., 2019). Cyclic fatigue is characterized by successive tensile and compression loads that the metal undergoes at the maximum point of flexion until it exceeds the limit that the instrument supports, thus causing fracture (ALCALDE et al., 2018a; SILVA et al., 2018a). In addition, the importance of Glide

Path has been increasingly reported in order to reduce the risk of transport and fracture of the instruments that will shaping the canal (DE-DEUS et al., 2016; HARTMANN et al., 2018).

However, even with so many instruments with good mechanical properties, that are capable of performing a correct shaping of the root canal and after adequate filling, in some situations, failures may occur, requiring endodontic retreatment (de CHEVIGNY et al., 2008; TORABINEJAD et al., 2009). The purpose of retreatment is to remove as much filling material as possible to allow a good sanification of the root canal system and a new filled in order to obtain successful treatment (DE-DEUS et al., 2018; DELAI et al., 2019). However, during the root canal retreatment, the instruments suffer great stress which can lead to their fracture. Therefore, the instruments selected to be used in this procedure must also have good mechanical properties to reduce the risk of fracture and consequently increase the chances of success (RODRIGUES et al., 2016; ROMEIRO et al., 2019).

Studies have shown that a significant amount of filling material remains in the root canal after the retreatment procedure independent of the type of instrument used (BRAMANTE et al., 2010; CAVENAGO et al., 2014; RODRIGUES et al., 2016). Based on this, agitation protocols of the irrigation solution have been proposed to potentiate the removal of the residual filling material and consequently to promote a more efficient cleaning of the root canal system. Ultrasonic inserts have been widely used for agitation of the irrigating solution during the preparation of the root canal and, more recently, in the canal retreatment procedure, showing excellent results (CAVENAGO et al., 2014; BERNARDES et al., 2016). In addition to the ultrasonic agitation, a new instrument called Eddy (VDW, Munich, Germany) was introduced for agitation of the irrigation solution after the chemomechanical preparation of the root canal which is coupled to a cavitator producing a sonic effect (ZENG et al 2018; DONNERMEYER et al., 2019). Another instrument that was produced specifically for the retreatment procedure is the XP-endo Finisher R (FKG Dentaire, La Chaux-de-Fonds, Switzerland), which is manufactured with a specific alloy called MaxWire (FKG Dentaire) that expands at body temperature, increasing the contact area (CAMPELLO et al., 2019; MACHADO et al., 2019).

Therefore, the objectives of this research, according to the sequence of the articles inserted in the thesis, were:

Article I and II - to evaluate, by micro-computed tomography (micro CT), the quality of the shaping of curved canals with the reciprocating systems Reciproc Blue 25.08 and 40.06, WaveOne Gold 25.07 and 35.06, ProDesign R 25.06 and 35.05, and to evaluate the resistance to cyclic fatigue of the same instruments, both new and after 3 uses in single-root teeth;

Article III - to evaluate, by microCT, the quality of the shaping of curved canals with the continuous rotation systems: BT-Race (10.06, 35.00 and 35.04); Sequence Rotary File (15.04, 25.06 and 35.04), ProDesign Logic (25.01, 25.06 and 35.05); and to evaluate the cyclic fatigue strength of the instruments size 35 (BT-Race 35.04, Sequence Rotary File 35.04 and ProDesign Logic 35.05) and the torsional fatigue strength of the instruments of glide path (BT-Race 10.06, Sequence Rotary File 15.04 and ProDesign Logic 25.01), both new and after 3 uses in curved single-root teeth;

Article IV - to evaluate the quality of retreatment of curved canals with the systems Reciproc 25.08 and 40.06, Reciproc Blue 25.08 and 40.06, Pro-R 25.08 and 40.06, ProDesign Logic RT 25.08 and 40.05; the cyclic fatigue strength of Reciproc 25.08, Reciproc Blue 25.08, Pro-R 25.08, ProDesign Logic RT 25.08, both new and after use in retreatment of one tooth and the working time for these instruments to reach the working length during retreatment;

Article V – and finally, to evaluate, by microCT, the efficiency in the removal of residual filling material of the different irrigation agitation protocols: continuous ultrasonic irrigation with Irrisafe and NiTiSonic, passive ultrasonic irrigation with the same inserts, the Eddy tip and XPendo Finisher R instrument.

2 Articles

2 ARTICLES

2.1 Article 1 - Effect of larger apical size on the quality of preparation in curved canals using reciprocating instruments with different heat thermal treatments

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Effect of larger apical size on the quality of preparation in curved canals using reciprocating instruments with different heat thermal treatments

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Running title: Quality of larger apical preparation

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ABSTRACT

Aim To evaluate the influence of larger apical canal enlargement in curved canals using reciprocating systems subjected to various heat treatments.

Methodology Ninety mandibular premolars with root curvatures ranging from 20° to 30° were selected and scanned by microcomputed tomography (micro-CT) before and after root canal preparation with reciprocating systems (n=30): Reciproc Blue (RB size 25, .08 taper and size 40, .06 taper, VDW, Munich, Germany), WaveOne Gold (WOG size 25, .07 taper and size 35, .06 taper, Dentsply Sirona, Ballaigues, Switzerland), and ProDesign R (PDR size 25, .06 taper and size 35, .05 taper, Easy Dental Equipment, Belo Horizonte, Brazil). Canal transportation, untouched areas, and apical and total root canal volumes were measured. Statistical analysis was performed with the non-parametric Kruskal-Wallis and Dunn's tests and a significance level set at 5%.

Results The between-group comparison revealed no significant difference in untouched areas, canal transportation, and apical root canal volume among the groups ($P>0.05$). However, WOG size 35, .06 taper was associated with a significant increase in the percentage of total canal volume in relation to the PDR size 35, .05 taper ($P<0.05$). The within-group comparison revealed a significant decrease in untouched areas, increase in apical and total root canal volume for all groups when using a larger instrument ($P<0.05$). There was no significant difference in transportation among groups and when a larger apical preparation was performed ($P>0.05$).

Conclusions Larger apical enlargement of curved canals was associated with a decrease in the untouched areas, an increase in root canal volume and maintenance of the canal trajectory. In addition, all systems were safe and provided similar root canal shapes.

INTRODUCTION

Chemomechanical preparation of root canals is one of the crucial steps in root canal treatment. Root canal preparation of curved canals is challenging (Wu *et al.* 2015, Liu & Wu 2016) and it is essential to preserve the original root canal anatomy, reducing the risk of canal transportation and perforations (Sant'Anna Júnior *et al.* 2014, Liu & Wu 2016, Marks Duarte *et al.* 2018).

Engine-driven nickel-titanium (NiTi) instruments have been widely used because of their safety and ability to shape curved canals. However, instrument fracture continues to be a concern and manufacturers have introduced several modifications (heat treatments, instrument design, and taper) to optimize the mechanical properties and the performance of instruments (Silva *et al.* 2016, Alcalde *et al.* 2017, De-Deus *et al.* 2017). At the same time, reciprocating kinematics favours greater cyclic fatigue resistance of NiTi instruments than does rotary motion (Lopes *et al.* 2013, Silva *et al.* 2018), even though reciprocating files are considered to be single-use instruments.

Reciproc Blue (VDW, Munich, Germany) is a reciprocating instrument manufactured by a heating/cooling process that induces the formation of a layer of titanium oxide, giving it a blue colour. They have an S-shaped cross-section and are composed of three instruments: size 25, .08 taper, size 40, .06 taper, and size 50, .05 taper (De-Deus *et al.* 2017, Alcalde *et al.* 2018). Another generation of reciprocating instruments is WaveOne Gold (Dentsply Sirona, Ballaigues, Switzerland), wich are manufactured by a new heat treatment that induces a Ti3Ni4 layer on the instrument's surface. The instruments have a parallelogram cross-section and are composed of four instruments: size 20, .07 taper, size 25, .07 taper, size 35, .06 taper, and size 45, .05 taper (Canali *et al.* 2018, Silva *et al.* 2018). ProDesign R (Easy Dental Equipment, Belo Horizonte, Brazil) is a reciprocating system composed of two instruments (size 25, .06 taper and size 35, .05 taper), which are manufactured with controlled memory (CM) NiTi technology and have an S-shaped cross-section (Silva *et al.* 2016, Alcalde *et al.* 2017).

The effect of larger apical enlargement is controversial. On the one hand the importance of preserving dentine and reducing the risk of fracture and the possibility of apical transportion should be take into account (Lopes *et al.* 2008, Capar *et al.* 2015). On the other hand, a decrease in the unprepared walls, improvement in irrigation, better disinfection of the canal and apical repair are benefits when larger apical enlargement is performed (Rodrigues *et al.* 2017, Jara *et al.* 2018, Pérez *et al.* 2018, Siqueira *et al.* 2018).

Several previous studies have evaluated the root canal preparation of Reciproc Blue, WaveOne Gold, and ProDesign R systems. However, only instrument size 25 were evaluated and there is a lack of information when evaluating the larger apical preparation with these systems (de Menezes *et al.* 2017, Alcalde *et al.* 2018, Keskin *et al.* 2018, Silva *et al.* 2018). In addition, there is concern whether larger instruments will maintain the canal trajectory, especially in situations where there are considerable curvatures.

Therefore, the aim of this study was to evaluate the influence of larger apical enlargement in curved canals on root canal volume, untouched areas, and canal transportation using Reciproc Bue size 25, .08 taper and size 40, .06 taper, WaveOne Gold size 25, .07 taper and size 35, .06 taper, and ProDesign R size 25, .06 taper and size 35, .05 taper files by micro-CT analysis. The null hypothesis tested is that there is no influence of the larger apical enlargement and reciprocating systems on the volume, untouched areas and canal transportion.

MATERIAL AND METHODS

Root canal preparation

The present study was approved by the Human Research Ethics Committee (process number: 88418518.4.0000.5417).

Ninety extracted human mandibular premolars, with complete apices, stored in 0.1% thymol solution were selected. Before root canal preparation, the teeth were scanned by micro-CT (SkyScan 1174v2; Bruker-microCT, Etiolles, Belgium). The teeth used were of type I in Vertucci's classification (Vertucci 1984) of the root canal anatomy and curvatures ranged from 20° to 30°, according to Schneider (1971).

Coronal access was performed and the working length was established by inserting a size K10 file (Dentsply Sirona, Ballaigues, Switzerland) until its tip was visualized through the apical foramen by means of a stereomicroscope (Stemi 2000C; Carl Zeiss, Jena, Germany) and the working length was established by reducing this by 1 mm. Afterwards, the teeth were subjected to biomechanical preparation of the root canal with the following systems (n=30):

Group 1 (RB size 25, .08 taper and size 40, .06 taper): The canal was irrigated with 2 mL of 2.5% sodium hypochlorite (NaOCl) and then instrumentation was performed using RB size 25, .08 taper instrument in "Reciproc all" configuration in the endodontic electric motor (VDW GmbH, Munich, Germany). The root canal was prepared using three in/out brushing motions. The canal was then irrigated with 2 mL of 2.5% NaOCl and root canal preparation was continued. These steps were accomplished until the working length could be reached. After root canal preparation, the canal was irrigated with 5 mL of 17% EDTA for 3 minutes and finally with 10 mL of saline solution. Then, the teeth were scanned by micro-CT. After micro-CT scanning, the root canal was prepared using RB size 40, .06 taper using the same technique described above. Then, a final micro-CT scanning was performed using the same parameters.

Group 2 (WOG size 25, .07 taper and size 35, .06 taper) and Group 3 (PDR size 25, .06 taper and size 35, .05 taper): The root canal was prepared using the same technique for the Reciproc group. WOG instruments were activated in "WaveOne ALL" configuration, while PDR was activated in "Reciproc All" configuration using a VDW electric motor.

Micro-CT scanning procedures

A 0.5-mm aluminum, 50 kV, 800 μA filter, 19.6 μm voxel size, 0.7 ° rotation angle and total 360° rotation were used as scanning parameters, producing 1304 x 1024 pixel images. Each scan resulted in images that were reconstructed using the NRecon v1.6.4.8 software (Bruker-microCT). To facilitate subsequent analyses and ensure that future scans could be performed in the same position as the initial one, a silicone mold was made for each tooth, so that it was always placed in the same position.

Measurement of volume and untouched areas

Pre- and post-instrumentation images were overlaid using the 3D registration function of the DataViewer software v.1.5.1 (Bruker microCT). The recorded images were processed in the CTAN software v.1.14.4 (Bruker microCT) to calculate the apical volume, which comprises the last 4 mm apically, and the total volume, which comprises the 10 mm volume of the canal from the root apex toward the orifice.

For the analysis of the untouched areas, 3D models were created with colour codes and the preoperative and postoperative images were recorded using an automatic image recorder. The apical surface area (last 4 mm) of the intact canal was determined based on the number of static objects, i.e., the marks present at the same position on the surface of the root canal before and after instrumentation. The data were converted and presented as an untouched area. The analysis of untouched areas was limited only to the apical region because it is the place where the curvature is found and it is the area of interest to observe the influence of the use of a larger instruments (Pérez *et al.* 2018).

Evaluation of root canal transportation

For the analysis of root canal transportation, axial sections corresponding to the distances of 1, 2, 3 and 4 mm from the apex were selected, corresponding to the curvature site. Transportation was calculated in millimetres using the formula ([X1-X2] - [Y1-Y2]) as described by Gambill *et al.* (1996), where X1 is the shortest distance between the inner wall of the root curvature and the lumen of the uninstrumented canal, X2 is the shortest distance between the inner wall of the root curvature and the canal lumen after instrumentation, Y1 is the shortest distance between the outer wall of the root curvature and the lumen of the uninstrumented canal, and Y2 is the shortest distance between the outer wall of the root curvature and the canal lumen after instrumentation. Preoperative and postoperative measurements were used for comparison, revealing the presence or absence of deviations in the anatomy of the canal and identifying the most affected region. According to this formula, a result of 0 (zero) indicated absence of root canal transportation. A negative result indicated transportation to the outer region of the curvature, while a positive result indicated transportation to the inner region of the curvature (Camargo *et al.* 2018, Pinheiro *et al.* 2018).

Statistical analysis

Statistical analysis was performed using the GraphPad Prism 5 program (La Jolla, CA, USA). The data obtained by the different evaluations were subjected to D'Agostino and Pearson's tests to verify the normal distribution of the data.

The data of volume, untouched areas, and transportation were evaluated by non-parametric Kruskal-Wallis and Dunn's tests for comparison among groups at each step. In the intragroup comparison for the same analyzes the Wilcoxcon test was used. The significance level was set at 5%.

RESULTS

The median, minimum and maximum values of the initial volume and percentage of increase in volume are represented in Table 1. There was no significant difference in the initial volume between the groups, either in the apical region or in the entire canal ($P>0.05$). There was no significantly difference among the groups regarding the apical and total of root canal volume for both apical preparation sizes evaluated ($P>0.05$), however, the use of larger instruments was associated with a significantly greater total volume for WOG size 35, .06 taper in comparison of PDR size 35, .05 taper ($P<0.05$). In the intragroup analysis, when the larger instruments were used, all the systems significantly increased the volume compared to the size 25 instruments ($P<0.05$).

The median, minimum and maximum values, and the percentage of untouched areas by the instruments are shown in Table 2. There were no significant differences among the groups in any of the apical preparation sizes ($P>0.05$). The within-group analysis revealed significant differences for all groups when larger apical preparation sizes were created, thus reducing the percentage of untouched areas by the instruments ($P<0.05$). Canal transportation is shown in Table 3. There was no significant difference among the groups for any of the apical preparation sizes ($P>0.05$).

Figure 1 shows representative image in micro-CT of the Reciproc Blue, WaveOne Gold and ProDesign R groups.

DISCUSSION

The aim of this study was to evaluate the influence of larger apical enlargement of curved canals on quality of the preparation using reciprocating instruments with several types of heat treatment (Reciproc Blue, WaveOne Gold, and ProDesign R). The null hypothesis tested was partially rejected because there was a significant difference in total volume among the reciprocating systems and larger apical enlargement influenced volume and untouched areas.

The presence of curved canals can be challenging during root canal preparation and are not always detected clearly on periapical radiographs, which can cause undesirable shaping errors (Vallabhaneni *et al.* 2017, Yammine *et al.* 2017). In this study, single-rooted mandibular premolars with root curvatures ranging from 20° to 30° were used. The specimens were paired according to the degree of curvature using the method proposed by Schneider (1971). In addition, the apical and total root canal volumes were measured previously and analyzed statistically, with no significant difference among the groups ($P>0.05$) (Table 1). In the same table, the percentage of volume increase reveal minimum and maximum values with high deviations, in all groups. This occurs when natural teeth are used as narrow and wide root canals were included in the sample. However, it is noted that there was a homogeneous distribution among the groups according to a statistical comparison between the initial volumes.

After root canal preparation, the increase in root canal volume, percentage of untouched areas, and canal transportation were assessed using instruments with a size 25 tip and complemented with large apical preparation sizes. The methodology has been extensively used in several previous studies because it is an accurate and non-destructible method (De-Deus *et al.* 2017, Duque *et al.* 2017, Camargo *et al.* 2018, Marks Duarte *et al.* 2018).

There was no significant difference in the percentage of volume increase (apical and total) among the three systems tested, except for the total volume after use of the larger instrument, where WOG size 35, .06 taper was associated with a higher volume ratio than PDR size 35, .05 taper ($P<0.05$). Untouched areas were evaluated on the apical portion because it is the most critical area for cleaning and shaping (Rodrigues *et al.* 2017, Siqueira *et al.* 2018). There was no significant difference among the groups ($P>0.05$). The possible explanation for the results obtained for volume and untouched areas can be related to the different design features of the instruments. Previous studies have shown that the cross-sectional area and taper of WOG is larger than that of the PDR (Alcalde *et al.* 2018, Silva *et al.* 2018), which could lead to less volume of metal. Therefore, it could be speculated that the greater metal volume could favour a greater increase in root canal volume and reduce the percentage of untouched areas. RB obtained intermediate results probably related to the design of the instrument. The RB has a cross section similar to the PDR, however, it has a larger taper in the apical millimetres.

Despite the difference in the NiTi alloy among the instruments, there were no significant differences in canal transportation ($P>0.05$). All systems had transportation at below 0.3 mm, which is considered by some studies to be the limit before a negative impact on clinical prognosis occurs (Camargo *et al.* 2018, Pinheiro *et al.* 2018). In addition, even after the use of larger instruments, the transportation of all groups did not exceed 0.15 mm, which is considered an acceptable value indicating a satisfactory maintenance of the canal trajectory (Peters 2004, Pinheiro *et al.* 2018). These results are in line with those of other studies that showed that RB and WOG had similar shaping ability (Bürklein *et al.* 2018, Keskin *et al.* 2018). In addition, heat-treated instruments tend to have a greater centering ability than conventional NiTi alloys (Duque *et al.* 2017, Ozyürek *et al.* 2017, Bürklein *et al.* 2018). There are no reports on the shaping ability of PDR instruments; however, Frota *et al.*

(2018) reported that PDR had a lower rate of foraminal deformation in comparison to Reciproc and WaveOne, which indicates a suitable centering ability. Although the results revealed a satisfactory maintenance of the canal trajectory, it can be observed in Table 3 that all systems had a tendency of root canal transportation toward the external root canal walls, regardless of the instruments diameter, which can also be observed in Figure 1. Therefore, in curved canals, even using heat-treated instruments, it is expected that there will be a deviation towards the outer wall of the curvature (Camargo *et al.* 2018).

The within-group comparison revealed a significant increase in root canal volume and a low percentage of untouched areas when the root canal was prepared with larger instruments ($P<0.05$). In addition, the root canal shape was maintained in comparison with size 25 instruments. These results corroborate those of other studies, which reported that apical preparation size can be obtained using instruments larger than size 25, allowing greater microbial reduction, flowability of the irrigating solution, reduction of debris at the apical portion and safely (Sant'Anna Júnior *et al.* 2014, Rodrigues *et al.* 2017, Pérez *et al.* 2018, Siqueira *et al.* 2018).

Manufacturers have introduced several modifications in design and alloy NiTi instruments to improve their mechanical properties and safety during root canal preparation, mainly in curved canals (Duque *et al.* 2017, Alcalde *et al.* 2018, Bürklein *et al.* 2018, Silva *et al.* 2018). In this study, larger apical enlargement with reciprocating heat-treated NiTi alloy instruments maintained the original shape of the canal with moderate curvature and were safe.

CONCLUSIONS

Larger apical enlargement significantly reduced the percentage of untouched areas and maintained the trajectory of curved canals. Additionally, Reciproc Blue, WaveOne Gold, and ProDesign R reciprocating systems had acceptable and similar root canal shaping abilities even in larger apical preparation sizes.

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CONFLICT OF INTEREST

The authors have stated explicitly that there are no conflicts of interest in connection with this article.

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FIGURE LEGENDS

Figure 1 Three-dimensional reconstructions of root canals of premolars theeth of the Reciproc Blue, WaveOne Gold and ProDesign R systems: before instrumentation (green), after instrumentation with intrument 25 tip size (red), and after preparation with larger instruments (35/40) (blue).

Table 1 Median, minimum and maximum values of the volume in mm3 and the percentage of volume increase after the use of the different reciprocating instruments.

	Region	Initial volume in mm3	% increase in volume after instrument 25	% increase in volume after instrument 35/40
Reciproc Blue	APICAL	0.26 (0.1-0.7)^{A}	42.18 (11.7-485)^{Aa}	169.80 (30.6-785)^{Ab}
WaveOne Gold		0.21 (0.1-0.9)^{A}	91.16 (4.7-374)^{Aa}	208.90 (10.6-762)^{Ab}
ProDesign R		0.29 (0.1-0.6)^{A}	40.67 (0.3-335)^{Aa}	95.53 (2.3-337)^{Ab}
Reciproc Blue	TOTAL	3.32 (1.3-6.6)^{A}	48.20 (2.1-139)^{Aa}	59.91 (22.5-158)^{ABb}
WaveOne Gold		2.76 (1.2-6.8)^{A}	39.51 (1.1-106)^{Aa}	108.90 (10.6-262)^{Bb}
ProDesign R		2.61 (1.6-6.3)^{A}	34.90 (0.3-95.7)^{Aa}	49.47 (1.2-97.8)^{Ab}

Different upper case letters in the same column indicate a significant difference among groups ($P<0.05$). Different lowercase letters in the same line indicate a significant intragroup difference ($P<0.05$).

Table 2 Median, minimum and maximum values of the percentage of untouched areas in the apical third after using different reciprocating instruments.

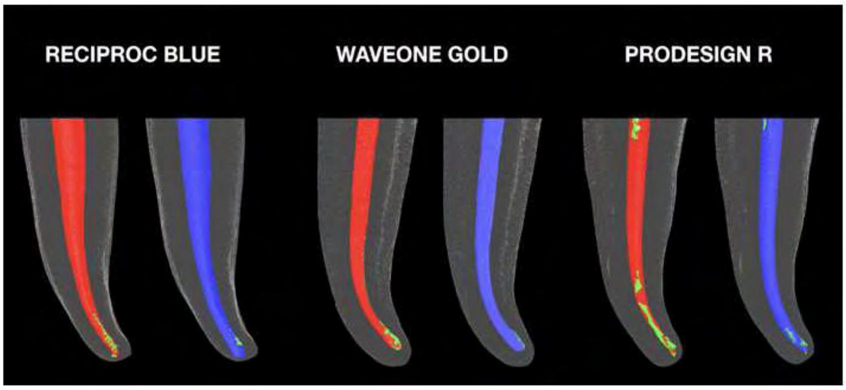
	Reciproc Blue 25	WaveOne Gold 25	ProDesig R 25	Reciproc Blue 40	WaveOne Gold 35	ProDesign R 35
% untouched areas (apical)	34.90[Aa] (14.1-62.1)	28.67[Aa] (1.2-77.5)	60.08[Aa] (2.5-84.7)	22.1[Ab] (6.7-46.2)	9.40[Ab] (0.5-68.6)	27.77[Ab] (1.1-58.2)

Different upper case letters indicate a significant difference among the groups according instruments caliber (P<0.05). Different lowercase letters indicate a significant intragroup difference (P<0.05).

Table 3 Mean, minimum and maximum values, in mm3, of the transport that occurred after the use of the different reciprocating instruments.

Regions	Reciproc Blue 25	WaveOne Gold 25	ProDesign R 25	Reciproc Blue 40	WaveOne Gold 35	ProDesign R 35
1 mm	-0.003^{Aa}	-0.080^{Aa}	-0.057^{Aa}	-0.043^{Aa}	-0.094^{Aa}	-0.073^{Aa}
	(-0.18/0.17)	(-0.13/0.98)	(-0.16/0.64)	(-0.39/0.09)	(-0.40/0.95)	(-0.19/0.75)
2 mm	0.032^{Aa}	0.002^{Aa}	0.001^{Aa}	0.044^{Aa}	-0.001^{Aa}	-0.033^{Aa}
	(-0.26/0.41)	(-0.17/0.20)	(-0.15/0.16)	(-0.26/0.29)	(-0.28/0.14)	(-0.19/0.31)
3 mm	-0.001^{Aa}	-0.044^{Aa}	-0.024^{Aa}	0.033^{Aa}	-0.045^{Aa}	0.012^{Aa}
	(-0.13/0.26)	(-0.17/0.09)	(-0.10/0.16)	(-0.13/0.13)	(-0.22/0.17)	(-0.92/0.23)
4 mm	0.001^{Aa}	-0.032^{Aa}	0.006^{Aa}	0.044^{Aa}	0.042^{Aa}	0.036^{Aa}
	(-0.31/0.38)	(-0.27/0.17)	(-0.26/0.28)	(-0.36/0.26)	(-0.22/0.18)	(-0,65/0.42)

*Positive indicates transport to the inner wall of the curvature. *Negative indicates transport to the outer wall of the curvature. Different upper case letters in the same line indicate a significant difference among the groups according instruments caliber (P<0.05). Different lowercase letters in the same line indicate a significant intragroup difference (P<0.05).


RECIPROC BLUE
WAVEONE GOLD
PRODESIGN R

2.2 Article 2 - Cyclic fatigue resistance of NiTi reciprocating instruments after simulated clinical use

The article presented in this thesis was submitted to the Journal of Endodontics

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Title: Cyclic fatigue resistance of NiTi reciprocating instruments after simulated clinical use

Article Type: Basic Research - Technology

Keywords: cyclic fatigue; NiTi alloy; reciprocating rotation.

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Manuscript Region of Origin: Latin & South America

Abstract: Introduction: To evaluate the cyclic fatigue resistence of different heat-treated NiTi reciprocating instruments in two different situations: new and instruments after preparing three curved canals. Methods: Ninety single-canal mandibular premolars with root curvatures ranging from 20° to 30° were selected and prepared with one of the tested systems (n=30): ProDesign R (PDR 25.06, Easy Dental Equipment, Belo Horizonte, Brazil), Reciproc Blue (RB 25.08, VDW, Munich, Germany) and WaveOne Gold (WOG 25.07, Dentsply-Sirona, Ballaigues, Switzerland). Each instrument was used to prepare three teeth and, after each use, the instruments were autoclaved. The used (n=10) and new instruments (n=10) were subjected to the cyclic fatigue test in an artificial canal with 30° angle and a 5-mm radius of curvature. Data were analysed using unpaired t test for intra-group comparison. For inter-group comparison ANOVA and Tukey's test for multiple comparisons were used. Results: The inter-group comparison of new instruments showed that PDR had the highest resistance to cyclic fatigue, followed by RB and WOG ($P<0.05$). Among used instruments, PDR and RB presented higher cyclic fatigue resistance than WOG ($P<0.05$). The intra-group comparison between new and used instruments showed that WOG and PDR instruments significantly reduced the cyclic fatigue resistance after clinical use ($P<0.05$); however, no differences were observed in RB instruments ($P>0.05$). Conclusions: New ProDesign R had the highest cyclic fatigue resistance while WaveOne Gold had the lowest one for new and used instruments. Clinical use influenced the cyclic fatigue resistance of ProDesign R and WaveOne Gold, but not of Reciproc Blue instruments.

.Title Page (Only file with author names)

Cyclic fatigue resistance of NiTi reciprocating instruments after simulated clinical use

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*Statement of Clinical Relevance (max 40 words)

STATEMENT OF CLINICAL RELEVANCE

In this study, all reciprocating systems tested were safe for use in 3 premolars with moderate curvature. In addition, new instruments of Prodesign R presented greater resistance to cyclic fatigue, followed by Reciproc Blue and Wave One Gold, respectively. Clinical use did not influence the cyclic fatigue of Reciproc Blue.

*Highlights (for review)

HIGHLIGHTS

Cyclic fatigue resistance of reciprocating instruments with different NiTi alloy were evaluated.

Influence of the clinical use on the cyclic fatigue resistance was evaluated.

New instruments of Prodesign R showed higher resistance to cyclic fatigue followed Reciproc Blue and Wave One Gold, respectively.

The clinical did not affect the Reciproc Blue.

Cyclic fatigue resistance of NiTi reciprocating instruments after simulated clinical use

ABSTRACT

Introduction: To evaluate the cyclic fatigue resistence of different heat-treated NiTi reciprocating instruments in two different situations: new and instruments after preparing three curved canals. **Methods:** Ninety single-canal mandibular premolars with root curvatures ranging from 20° to 30° were selected and prepared with one of the tested systems (n=30): ProDesign R (PDR 25.06, Easy Dental Equipment, Belo Horizonte, Brazil), Reciproc Blue (RB 25.08, VDW, Munich, Germany) and WaveOne Gold (WOG 25.07, Dentsply-Sirona, Ballaigues, Switzerland). Each instrument was used to prepare three teeth and, after each use, the instruments were autoclaved. The used (n=10) and new instruments (n=10) were subjected to the cyclic fatigue test in an artificial canal with 30° angle and a 5-mm radius of curvature. Data were analysed using unpaired t test for intra-group comparison. For inter-group comparison ANOVA and Tukey's test for multiple comparisons were used. **Results:** The inter-group comparison of new instruments showed that PDR had the highest resistance to cyclic fatigue, followed by RB and WOG ($P<0.05$). Among used instruments, PDR and RB presented higher cyclic fatigue resistance than WOG ($P<0.05$). The intra-group comparison between new and used instruments showed that WOG and PDR instruments significantly reduced the cyclic fatigue resistance after clinical use ($P<0.05$); however, no differences were observed in RB instruments ($P>0.05$). **Conclusions:** New ProDesign R had the highest cyclic fatigue resistance while WaveOne Gold had the lowest one for new and used instruments. Clinical use influenced the cyclic fatigue resistance of ProDesign R and WaveOne Gold, but not of Reciproc Blue instruments.

Keywords: cyclic fatigue; NiTi alloy; reciprocating rotation.

INTRODUCTION

Nickel-titanium (NiTi) instruments have been widely used for root canal preparation; however, these instruments appear to be vulnerable to deformations and/or fractures, which may contribute negatively to treatment prognosis (1-3). To overcome these drawbacks, improvements and modifications in instruments design, NiTi alloy and kinematics has been proposed (4-6). Several thermomechanical NiTi treatments have been suggested to produce instruments with increased resistance to fatigue, flexibility and capacity of self-centering in the canal during preparation (4,7). Moreover, reciprocating motion has been proposed to improve cyclic fatigue life and the torsional resistance of NiTi instruments (7,8). ProDesign R (Easy Dental Equipments, Belo Horizonte, Brazil), Reciproc Blue (VDW, Munich, Germany) and WaveOne Gold (Dentsply-Sirona, Ballaigues, Switzerland) are examples of heat-treated NiTi reciprocating instruments. Reciproc Blue are manufactured by a heating/cooling process that induces the formation of a titanium oxide layer, which gives a blue color to the instrument (5,6). WaveOne Gold are manufactured by a similar process but with a deposition of a gold color titanium oxide layer (7,9). ProDesign R are manufactured in a Control-Memory like NiTi alloy (2,10).

NiTi instruments may fracture in curved canals because of cyclic or torsional fatigue (4,11). Cyclic fatigue occurs by repetitive cycles of compressive and tensile stresses during instrument rotation of a curved canal (6,11). The type of NiTi alloy and activation kinematics (3,8,10) influences cyclic fatigue resisntance of NiTi instruments. Moreover, authors have reported that clinical use, exposition to sodium hypochlorite and autoclaving sterilization procedures can affect the mechanical properties of NiTi instruments, decreasing cyclic fatigue resistance of these instruments (12,13).

Considering that NiTi instruments are generally reused in clinical practice for the most different reasons (12) and that recent publications pointed out the possibility of using NiTi reciprocating instruments in up to three posterior teeth (14), the aim of the present study was to evaluate the cyclic fatigue resistance of three different thermally-treated NiTi reciprocating instruments, ProDesign R [tip 25, .06 taper (Easy Dental Equipments, Belo Horizonte, Brazil)], Reciproc Blue [tip 25, .08v taper (VDW, Munich, Germany)] and WaveOne Gold [tip 25, 0.07v taper (Dentsply Sirona, Ballaigues, Switzerland) in two different situations: new instruments without use and instruments tested after preparing three single-canalled curved mandibular premolars. The null hypothesis tested were:

I- There are no differences in the cyclic fatigue resistance among the different tested instruments.

II- There are no differences in the cyclic fatigue resistance between new instruments and those that have been stressed with root canal preparations;

METHODS

A sample of 60 NiTi instruments (length = 25 mm) of 3 systems (n = 20 per system) were used in this study as follows: ProDesign R (tip 25, .06 taper), Reciproc Blue (tip 25, .08v taper) and WaveOne Gold (tip 25, 0.07v taper). Before root canal preparation, every instrument was inspected for defects or deformities under a stereomicroscope (Carl Zeiss, LLC, Oberkochen, Germany) at 16X magnification; none were discarded.

Root canal preparation

Ninety extracted human mandibular premolars classified as type I in Vertucci's (15) classification of the root canal anatomy and curvatures ranged from 20° to 30°, according to Schneider (16) were selected and distributed equally in to three groups (n=30) accordingly the system used to prepare the root canals: PDR 25.06, RB 25.08 and WOG 25.07.

The working length was established by introducing 10K file until it could be detected through the apical foramen by stereomicroscope and subtracting 1 mm. The root canal was prepared using a crown-down technique and in/out movements, following the recommendations of each manufacturer. During the biomechanical preparation the canals were irrigated with 10 mL of 2.5% sodium hypochlorite. The same instrument was used in 3 different teeth and, between each use, the instrument was subjected to adequate cleaning and sterilization at 121° C, at a pressure of 30 psi, for 20 min, and then to drying for 15 min.

Cyclic Fatigue Test

The cyclic fatigue tests were performed using a custom-made device that simulates an artificial curved canal as previously described (3,17). The artificial canal provides an artificial canal trajectory with a 30° angle of curvature and a 5-mm radius of curvature. The curvature of the stainless steel artificial canal was fitted onto a guide cylinder made of the same material. Both the arch and the guide cylinder had a 1-mm-deep groove, served as a guide path for the instrument, which remained curved and free to rotate between the cylinder and external arch.

New and used instruments (n=10 per system and per condition) were activated by using a 6:1 reduction handpiece (Sirona Dental Systems GmbH, Bensheim, Germany) powered by a torque-controlled motor (Silver Reciproc, VDW) using the preset programs ''RECIPROC ALL''. The present programs were selected according to the manufacturers' instructions. To reduce the friction of the instrument as it came into contact with the artificial canal walls, a special high-flow synthetic oil prepared for lubrication of mechanical parts (Super Oil; Singer Co Ltd, Elizabethport, NJ) was applied. The time from motor activation was recorded and stopped as soon as a fracture was detected visually and/or audibly on a digital timer. During this step, a video recording was performed simultaneously, and the recordings were observed to ensure the accurate time of instrument fracture. Then, the number of cycles was obtained by multiplying the number of rotations per minute (RPM) x time/60 (number of rotations per seconds).

Scanning electron microscopy

After the cyclic fatigue test, the fractured surface of the new and used instruments were examined by scanning electron microscope (JSM-TLLOA; JEOL, Tokyo, Japan) at 250x magnification, to evaluate the topographic characteristics.

Statistical analysis

Statistical analysis was performed using the GraphPad Prism 5 program (La Jolla, CA, USA). The data were subjected to D'Agostino and Pearson's tests to verify the normal distribution. After confirming normality, data were analysed using unpaired t test for intra-group comparison. For inter-group comparison ANOVA and Tukey's test for multiple comparisons were used. The level of significance was set at 5%.

RESULTS

The mean and standard deviations of the cyclic fatigue resistance of the new instruments and after three simulated clinical uses are presented in **Table 1**. The inter-group comparison of new instruments showed that ProDesign R had the highest resistance to cyclic fatigue, followed by Reciproc Blue and WaveOne Gold ($P<0.05$). Among used instruments, ProDesign R and Reciproc Blue presented higher cyclic fatigue resistance than WaveOne Gold ($P<0.05$). The intra-group comparison between new and used instruments showed that WaveOne Gold and ProDesign R instruments significantly reduced the cyclic fatigue resistance after clinical use ($P<0.05$); however, no differences were observed between new and used Reciproc Blue instruments ($P>0.05$).

Scanning electron microscopy of the fractured surface showed similar and typical features of cyclic fatigue for new and used instruments. All the instruments displayed fractured surfaces with microvoids, morphologic characteristics of ductile fracture (**Figure 1**).

DISCUSSION

In this study, the methodology used to evaluate cyclic fatigue was already validated and used in numerous articles published in peerreviewed journals (3,17). It is important to highlight that there are no specifications or international standards for the evaluation of this propriety in NiTi endodontic instruments. Although previous studies suggested a dynamic cyclic fatigue model to test the cyclic fatigue resistance of NiTi instruments (18,19), as it models approximate a clinical use, this model has some limitations. First, the instruments being tested are not constrained in a precise trajectory. Moreover, the speed and amplitude of the axial movements could be standardized in a dynamic model, but these variables are completely subjective and it is doubtfull that they are constant and reproducible in a clinical situation (20). For this reason, aiming to minimize confounding causes by other mechanisms of instrument separation apart from cyclic fatigue, the static model was selected in the present study.

The aim of the present study was to evaluate the cyclic fatigue resistance of three different thermally-treated NiTi reciprocating instruments, ProDesign R, Reciproc Blue and WaveOne Gold in two different situations: new instruments without use and instruments tested after preparing three single-canalled curved mandibular premolars. The first results of this study demonstrated differences in the cyclic fatigue resistance between the different instruments in both new and after simulated clinical use conditions. Therefore, the first null hypothesis was rejected. In fact, these results corroborate with several previously published studies that pointed out differences in the cyclic fatigue resistance between different instruments (2,5-7). Silva et al (7) demonstrated that ProDesign R showed the longer cyclic fatigue resistance, followed by Reciproc Blue and WaveOne Gold. Similar results were also observed by Alcalde et al (6) that also compared those three instruments and also demonstrated that ProDesign R outperformed Reciproc Blue and WaveOne Gold, regarding the cyclic fatigue resistance. The cyclic fatigue resistance dependes on several factors such as instrument design (tip diameter, taper, metal mass, cross-section) and NiTi alloy (3-7). Although all tested instruments have similar tip diameter (0.25mm), remarkable differences in its NiTi alloy, cross-section design and taper might explain the present results. ProDesign R is manufactured with CM technology, which has greater flexibility and cyclic fatigue resistance when compared to blue or gold NiTi treatments (2,6,10). In addition, ProDesign R instruments have a smaller taper (0.06) than Reciproc Blue (0.08) and WaveOne Gold (0.07), which could affect mechanical properties during the cyclic fatigue test (6,21). The Reciproc Blue instruments presented greater cyclic fatigue resistance than did WaveOne Gold instruments ($P<0.05$). Although Reciproc Blue has a greater taper than WaveOne Gold, the S-shaped cross-section of Reciproc Blue led to a smaller metal mass volume than did the parallelogram cross-section of WaveOne Gold, which increases the flexibility of the instruments and might corroborate with the present results (6,7).

The second results of the present study demonstrated that ProDesign R and WaveOne Gold had significantly lower cyclic fatigue resisntance after simulated clinical use. However, no differences were observed for Reciproc Blue new and used instruments. Therefore, the second null hypothesis was partially rejected. Previously published studies demonstrated that the cyclic fatigue resistance may decline after simulated clinical use (22-24). However, to the best of the author's knowledge, this is the first study where reciprocating heat-treated NiTi instruments were tested after simulated clinical use. It is important to point-out that, even reducing the cyclic fatigue resistance of ProDesign R and WaveOne Gold instruments, no fracture was observed for none of the tested instruments in the present study. However, the present results demonstrated that ProDesign R and Reciproc Blue could be safer than WaveOne Gold during root canal preparation of curved canals, reducing the risk of cyclic fatigue failures.

In the present study, a 2.5% NaOCl solution was used during root canal preparation and the instruments were sterilized after each use to simulate clinical conditions. Bulem et al (25) reported that immersion in 2.5% NaOCl and sterilization did not affect the cyclic fatigue resistance of NiTi instruments. Conversely, Pedullà et al (13) reported that NaOCl immersion and sterilization decreased the resistance of Twisted Files to cyclic fatigue but it did not affect Hyflex CM instruments. Champa et al (26) reported that the use of NaOCl and sterilization decrease the cyclic fatigue resistance of Reciproc and WaveOne in artificial canals with 30° of curvature. The reports mentioned above corroborate our findings. The different results obtained for the currently tested instruments may be explained by differences inherents to the instruments such as heat-treatment and design, that could be more or less affected by NaOCl exposition, autoclave sterilization process and simulated clinical use.

In the present study, the simulated clinical use was performed preparing root canals of curved mandibular premolars. Despite the anatomic variation and the complex internal root canal anatomy, this study made many efforts to standardize the samples in order to reduce possible variables and the biases. One may argue that slight differences in the selected teeth could affect the comparison among the instruments; however, this direct comparison can be performed in an unbiased way using the baseline control groups (instruments without clinical use).

The SEM analysis showed the typical fractographic appearance of cyclic fatigue of new and used instruments for the 3 brands. After the cyclic fatigue test, the instruments showed crack initiation areas and overload (fast fracture) zones, with numerous dimples spread on the fractured surface (6,27).

CONCLUSIONS

New ProDesign R had the highest cyclic fatigue resistance while WaveOne Gold had the lowest one for new and used instruments. Clinical use influenced the cyclic fatigue resistance of ProDesign R and WaveOne Gold, but not of Reciproc Blue instruments.

ACKNOWLEDGEMENTS

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CONFLICT OF INTEREST

The authors have stated explicitly that there are no conflicts of interest in connection with this article.

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FIGURE LEGENDS

Figure 1. Scanning electron microscopy images of the fractured surfaces of separated fragments of the new and used instruments of ProDesign R 25.06, Reciproc Blue 25.08 and WaveOne Gold 25.07 after cyclic fatigue testing. The images show numerous dimples spread on the fractured surfaces, which constitute a typical feature of ductile fracture.

Figure
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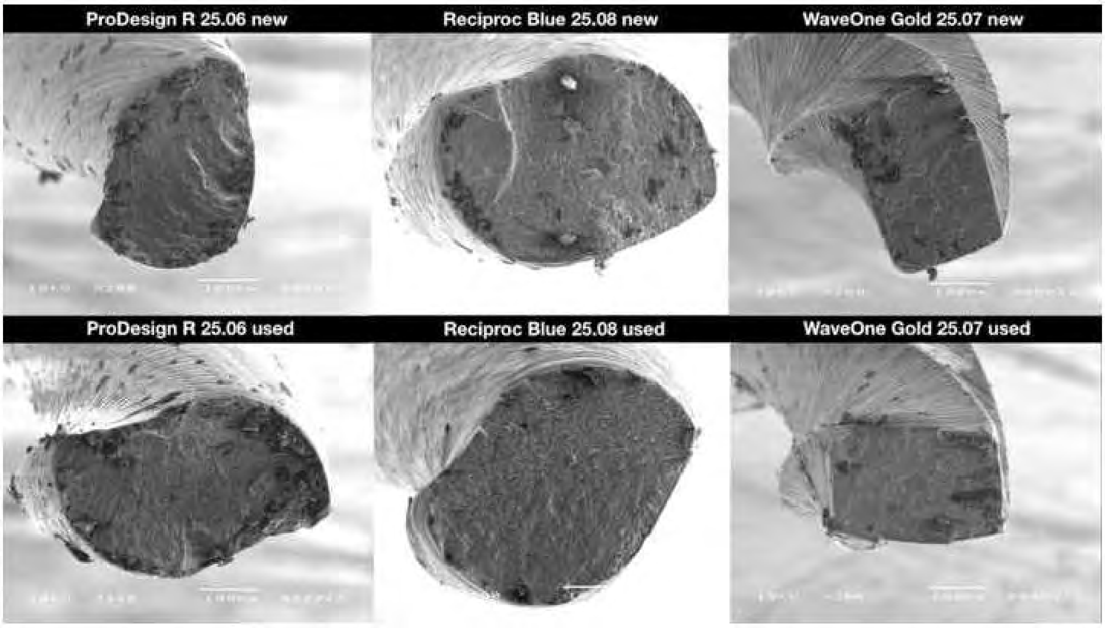

Letter with Signatures

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18th Feb 2019

To the Editor of the Journal of Endodontics,

We are submitting a manuscript entitled "**Cyclic fatigue resistance of NiTi reciprocating instruments after simulated clinical use**", which has been approved by all of the authors. This is an original manuscript that has not been previously published either in totality or in part, including the illustrations and that it is not under consideration for publication elsewhere. In consideration of the editors of the Journal of Endodontics taking action in reviewing and editing this submission, the authors undersigned hereby transfer, assign or otherwise convey all copyright ownership.

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Table

Table 1. Mean values of time (in seconds), number of cycles (NCF) of new instruments and after three uses.

	Cyclic Fatigue							
Instruments	New instruments				Used instruments			
	Time (seconds)		Cycles (NCF)		Time (seconds)		Cycles (NCF)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
PDR 25.06	1298.0 ^{a,A}	146.2	7566.0 ^{a,A}	852.6	699.2 ^{a,B}	77.55	4076.0 ^{a,B}	452.1
RB 25.08	694.1 ^{b,A}	69.05	3471.0 ^{b,A}	345.3	749.0 ^{a,A}	31.92	3745.0 ^{a,A}	159.6
WOG 25.07	264.4 ^{c,A}	29.94	1541.0 ^{c,A}	121.7	154.5 ^{b,B}	13.27	901.0 ^{b,B}	110.2

SD, stan
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n.

Different lowercase letters in the same column indicate statistical differences among groups (P<0.05).

Different capital letters on the same line indicate statistical differences between new and used instruments of the same group (P<0.05).

2.3 Article 3 - Evaluation of root canal preparation and mechanical properties of NiTi rotary instruments manufactured with different types of NiTi alloys

The article presented in this thesis was submitted to the Clinical Oral Investigations

Clinical Oral Investigations

EVALUATION OF ROOT CANAL PREPARATION AND MECHANICAL PROPERTIES OF NITI ROTARY INSTRUMENTS MANUFACTURED WITH DIFFERENT TYPES OF NITI ALLOYS

--Manuscript Draft--

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Abstract:	Objectives To evaluate the quality of root canal preparation of curved canals, torsional fatigue and cyclic fatigue, of instruments new and after clinical use, of rotary systems manufactured with different NiTi alloys. Materials and methods Ninety single-rooted canals with curvatures of 15 to 30o were scanned and divided into three groups according to the rotary system used (n=30): BT-Race-BTR (10.06, 35.00, and 35.04), SequenceRotaryFile-SRF (15.04, 25.06, and 35.04), and ProDesignLogic-PDL (25.01, 25.06, and 35.05). The teeth were scanned again and analyzed for volume, canal transportation, and centering ability. During preparation, each system was used on three teeth. Torsional fatigue of glidepath instruments and cyclic fatigue of the finishing instrument were analyzed. These analyses were performed with new (n=10) and used (n=10) instruments. Results Volume increase, canal transportation, and centering ability did not present significant differences among the groups (P>0.05). The torsional test showed that SRF15.04 presented the highest torque values for both new and used instruments, followed by PDL25.01 and BTR10.06 (P<0.05). PDL25.01, both new and used, presented higher values of angular deflection followed by SRF15.04 and BTR10.06 (P<0.05). In cyclic fatigue, PDL35.05, both new and used, presented longer time and larger number of cycles than did SRF35.04 and BTR35.04 (P<0.05). Clinical use

	affected BTR in torsional fatigue and cyclic fatigue was not significantly affected. Conclusions All rotary systems were able to prepare the curved canals satisfactorily and used safely on three teeth. Torsional fatigue, SRF15.04 presented higher torque and PDL25.01 higher angular deflection. BTR10.06 was the most affected by clinical use. PDL35.05 presented greater resistance to cyclic fatigue. Clinical relevance In clinical practice, rotary instruments have been reused in shaping root canal. Therefore, it is necessary to know the quality of preparation and safety of these systems to minimize the risks of accidents.
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EVALUATION OF ROOT CANAL PREPARATION AND MECHANICAL PROPERTIES OF NITI ROTARY INSTRUMENTS MANUFACTURED WITH DIFFERENT TYPES OF NITI ALLOYS

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ABSTRACT

Objectives To evaluate the quality of root canal preparation of curved canals, torsional fatigue and cyclic fatigue, of instruments new and after clinical use, of rotary systems manufactured with different NiTi alloys.

Materials and methods Ninety single-rooted canals with curvatures of 15 to 30° were scanned and divided into three groups according to the rotary system used (n=30): BT-Race-BTR (10.06, 35.00, and 35.04), SequenceRotaryFile-SRF (15.04, 25.06, and 35.04), and ProDesignLogic-PDL (25.01, 25.06, and 35.05). The teeth were scanned again and analyzed for volume, canal transportation, and centering ability. During preparation, each system was used on three teeth. Torsional fatigue of glidepath instruments and cyclic fatigue of the finishing instrument were analyzed. These analyses were performed with new (n=10) and used (n=10) instruments.

Results Volume increase, canal transportation, and centering ability did not present significant differences among the groups (P>0.05). The torsional test showed that SRF15.04 presented the highest torque values for both new and used instruments, followed by PDL25.01 and BTR10.06 (P<0.05). PDL25.01, both new and used, presented higher values of angular deflection followed by SRF15.04 and BTR10.06 (P<0.05). In cyclic fatigue, PDL35.05, both new and used, presented longer time and larger number of cycles than did SRF35.04 and BTR35.04 (P<0.05). Clinical use affected BTR in torsional fatigue and cyclic fatigue was not significantly affected.

Conclusions All rotary systems were able to prepare the curved canals satisfactorily and used safely on three teeth. Torsional fatigue, SRF15.04 presented higher torque and PDL25.01 higher angular deflection. BTR10.06 was the most affected by clinical use. PDL35.05 presented greater resistance to cyclic fatigue.

Clinical relevance In clinical practice, rotary instruments have been reused in shaping root canal. Therefore, it is necessary to know the quality of preparation and safety of these systems to minimize the risks of accidents.

Keywords: rotary motion, microcomputed tomography, root canal preparation, cyclic fatigue, torsional strength.

INTRODUCTION

In recent years, several modifications in alloys and in the design of nickel-titanium (NiTi) instruments have been carried out in order to improve the performance of these instruments, especially in cases of curved canals, thus avoiding canal transportation and instrument fractures, which could compromise the success of endodontic treatment [1,2].

During root canal preparation, successive stages are carried out using instruments with different purposes. One of these steps is the glide path, which consists of creating a path from the canal entrance to the apical foramen [3,4]. Nowadays, several rotary systems have specific files for this step. However, because they are used at the beginning of the procedure, these instruments are more prone to torsional stresses [4,5]. Torsional stress occurs when the tip of the instrument attaches to the dentin wall and continues to rotate until fracture occurs [6,7].

After glide path preparation, another important step of endodontic treatment is initiated: dilation of the canal. This step becomes even more challenging when the tooth has a curved canal, because the instrument, at the maximum bending point, is subjected to tensile/compressive forces. If these forces, which are cumulative, exceed the maximum value the instrument can withstand, the instrument will fracture due to cyclic fatigue [6,7]. Thus, several instruments have been introduced in the market. BT-RaCe (FKG Dentaire, La Chaux-de-Fonds, Switzerland) is a rotary system with a new tip design – booster tip – which, according to the manufacturer, facilitates the advancement of the instrument and reduces the risks of canal transportation, improving centering ability. In addition, it is a system made of a conventional NiTi alloy and with an electrochemical treatment on its surface. The BT-RaCe system presents one glide path instrument with size 10, 0.06 taper, and two instruments for canal preparation with size 35, 0.00 taper, and size 35, 0.04 taper [8-10].

Another rotary system recently introduced in the market is the Sequence Rotary File (MKLife, Porto Alegre, RS, Brazil), with heat-treated instruments using Blue technology. This system consists of a glide path with file size 15 and 0.04 taper; and three shaping instruments with size 20, 0.06 taper, size 25, 0.06 taper, and size 35, 0.04 taper. Except for instrument 15.04, which has a quadrangular cross section, the other instruments have a convex triangular cross section. However, there are no studies in the literature evaluating this system.

ProDesign Logic (Easy Dental Equipment, Belo Horizonte, MG, Brazil) is a continuous rotation system manufactured in NiTi with controlled memory (CM). This system has a glide path instrument of size 25, 0.01 taper, with a quadrangular section, and instruments for preparing the canal in size 25, 0.06 taper, and in size 35, 0.05 taper, with an S-shaped cross-section [11,12].

The literature has shown the possibility of reusing mechanized systems safely [13,14]. However, it is unknown to what extent this clinical use affects the mechanical properties of instruments. Considering the scarcity of studies in the literature evaluating the quality of preparation and mechanical properties of these systems, and given the importance of elucidating for the clinician the safety these instruments provide during root canal preparation, the objective of this study was to evaluate the quality of preparation of curved canals, torsional fatigue of the glide path instrument, and cyclic fatigue of the final finishing instrument of continuous rotation systems with different types of NiTi alloys. The null hypotheses tested were as follows: (1) there would be no difference in quality of preparation among the different systems, (2) there would be no difference in torsional fatigue strength of the different glide path instruments, (3) there would be no difference in cyclic fatigue strength among the finishing instruments of the tested systems, and (4) the would be no influence of simulated clinical use on the mechanical properties of instruments.

METHODS

The present study was approved by the Human Research Ethics Committee (process number: 88418518.4.0000.5417).

Tooth preparation

Ninety extracted human single-rooted mandibular teeth with canals with a closed apex, stored in a 0.1% thymol solution, were selected. The following inclusion criteria were used: type I canal configuration according to Vertucci's classification [15], and an angle of curvature between 15° and 30° according to Schneider's method [16]. Initially, the teeth were scanned using computed microtomography (SkyScan 1174v2; Bruker-micro-CT, Ethiolles, Belgium) according to predefined parameters.

After coronal access, working length (WL) was established by inserting a K-type file #06 (Dentsply-Maillefer, Ballaigues, Switzerland) until its tip was visualized in the foramen by means of a stereo microscope (Stemi 2000C; Carl Zeiss, Jena, Germany), decreasing 1 millimeter. Subsequently, the teeth were subjected to biomechanical root canal preparation with the following rotary systems (n=30):

Group 1: BT-Race (BTR) - The canal was irrigated with 2 mL of 2.5% sodium hypochlorite (NaOCl) and then instrumentation was performed with the BTR system following the sequence proposed by the manufacturer. BTR 10.06, 35.00, and 35.04 instruments were used in continuous rotation at a speed of 800 rpm and 1.5 N torque using an endodontic electric motor (VDW GmbH, Munich, Germany). For each instrument, three in/out movements were performed in the apical direction. The instrument was removed; irrigation was performed with 2 mL of 2.5% NaOCl; and instrumentation was performed again, as described above, until WL was reached.

Group 2: Sequence Rotary File (SRF) - The procedure was similar to that described above, but SRF 15.04, 25.06, and 35.04 instruments were used in continuous rotation, with the glide path 15.04 instrument at a speed of 350 rpm and 1 N torque, and the shaping instruments 25.06 and 35.04 at a speed of 500 rpm and 2 N torque, using VDW endodontic electric motor, according to the manufacturer's recommendations.

Group 3: ProDesign Logic (PDL) – A procedure similar to the previous two was performed using PDL instruments 25.01, 25.06, and 35.05 in continuous rotation, with glide path 25.01 instrument at a speed of 350 rpm and 1 N torque and shaping instruments 25.06 and 35.05 at a speed of 950 rpm and 4 N torque, using VDW endodontic electric motor, according to the manufacturer's instructions.

At the end of the instrumentation, the canals were irrigated with 5 mL of 17% EDTA (Biodynamics, Ibiporã, Paraná, Brazil) for 3 minutes to remove the smear layer, then washed with 5 mL of saline solution, dried with absorbent paper points #35 and subjected to computerized microtomography (micro-CT) using the same initial parameters.

Micro-CT procedures

A 0.5-mm aluminum filter, 50 kV, 800 µA, voxel size of 19.6 µm, rotation angle of 0.7, and total rotation of 360° were used as scanning parameters, producing images with a resolution of 1304 x 1024 pixels. Each scan resulted in images that were reconstructed using NRecon software v1.6.4.8 (Bruker-micro-CT). A silicone mold was made for each tooth to ensure scanning in the same position so as not to interfere in the subsequent analysis.

Volume measurement

The pre- and post-instrumentation images were superimposed using the 3D recording function of DataViewer v.1.5.1 (Bruker micro-CT) software. The recorded images were processed in CTAN software v.1.14.4 (Bruker micro-CT) to calculate the apical volume, which comprises the last four apical millimeters, and the total volume, which comprises the 10-mm volume of the canal from the root apex to the cervical direction.

Evaluation of root canal transportation

For the analysis of root canal transportation, axial sections corresponding to distances of 1, 2, 3, and 4 mm from the apex, which indicate the region of the curvature, were selected. Transportation was calculated in millimeters using the formula ([X1-X2] - [Y1-Y2]) as described by Gambill et al. [17], where X1 is the shortest distance between the inner wall of the root curvature and the lumen of the uninstrumented canal; X2 is the shortest distance between the inner wall of the root curvature and the lumen of the canal after being instrumented; Y1 is the shortest distance between the outer wall of the root curvature and the lumen of the uninstrumented canal; and Y2 is the shortest distance between the outer wall of the root curvature and the lumen of the canal after being instrumented. According to this formula, a result of 0 (zero) indicated no root canal transportation; a negative result indicated transportation to the outer region of the curvature; and a positive result indicated transportation to the inner region of the curvature.

Evaluation of centering ability

The measurements of X1, Y1, X2, and Y2 at the apical third were used to evaluate centering ability, according to the equation suggested by Gambill et al. [17]: (X1-X2)/(Y1-Y2) or (Y1-Y2)/(X1-X2). The lowest value was considered the numerator. A result of 1 indicated perfect centering ability.

Torsional fatigue test

During biomechanical preparation, the same system was used on three different teeth, and, after use, the instruments were always subjected to adequate cleaning and sterilization at 134° C, with a pressure of 30 psi, for 20 minutes, and then dried for 15 minutes.

The torsion test was based on ISO 3630-1 (1992), where a specific machine was used, as described in detail in other studies [18,19]. The test was performed only with the glide path files of the systems used in this study (BTR 10.06, SRF 15.04, and PDL 25.01), both new (n=10) and the instruments used in biomechanical preparation (n=10). The test established the average torque and maximum angular deflection values before instrument fracture. The torque values were evaluated by measuring the force exerted on a small load cell by a lever arm connected to the axis of torsion. The angle of rotation was measured and controlled by a resistive angle transducer connected to a process controller. To perform the test, the instrument handle was removed at the point where it was attached to the shaft. The end of the shaft was attached to a mandrel connected to a reversible gear motor. Three millimeters of the instrument tip was attached to another mandrel with brass jaws to prevent slippage.

The clockwise rotation speed was set to 2 rpm. The continuous recording of torque and angular rotation was monitored and the final torsional force and angular rotation (°) were provided by a specifically designed computer program (Analogica, Belo Horizonte, MG, Brazil) and recorded [19].

Cyclic fatigue test

For the cyclic fatigue test, the finishing instruments (BTR 35.04, SRF 35.04, and PDL 35.05) of each system used in biomechanical preparation were used and the methodology for this test were based on what was described and used by Marks Duarte et al. [2] and Klymus et al. [20]. However, an angle of 30° and a radius of 5 mm were used in the test. The cyclic fatigue test was performed with the new instruments (n=10) and with the instruments used during biomechanical preparation (n=10). Time (in seconds) was measured with a digital stopwatch until instrument fracture. A video was recorded simultaneously to obtain the exact moment when the fracture occurred. Then, the number of cycles was also calculated until instrument fracture.

Statistical analysis

The statistical analysis was performed using GraphPad Prism 5 software (La Jolla, CA, USA). The data were subjected to D'Agostino-Pearson test to verify if there was a normal distribution.

Regarding volume, canal transportation, and centering ability, the data were not normally distributed. The non-parametric Kruskal-Wallis and Dunn's tests were used. In torsional and cyclic fatigue tests, the data had a normal distribution and were subjected to ANOVA and Tukey's parametric tests. A significance level of 5% was considered for all tests.

RESULTS

The median, minimum and maximum values of baseline and final volume, and percent increase in volume are presented in Table 1. Baseline volume and percent increase in volume did not show significant difference in apical and total root canal volume ($P>0.05$) among the groups. However, in the within-group comparison, there was a significant difference between baseline and final volume, both for apical and total volume, in all groups ($P<0.05$).

The median, minimum and maximum values of canal transportation, and centering ability are shown in Table 2. There was no significant difference among the groups for any of the analyses ($P>0.05$). All groups presented small canal transportation and satisfactory centering ability.

The torsional strength (maximum load torque and angle of rotation) of the instruments is shown in Table 3. Among the instruments, SRF 15.04, new and after clinical use, had higher torsional strength than did PDL 25.01 and BTR 10.06, respectively ($P<0.05$). In relation to the angle of rotation, regarding both new and used instruments, PDL showed higher values, followed by SRF and BTR, respectively ($P<0.05$). The within-group comparison between new and used instruments showed that BTR significantly reduced torque strength ($P<0.05$), while SRF and PDL were not affected by clinical use ($P>0.05$). In relation to the angle of rotation, all instruments were significantly affected by clinical use ($P<0.05$).

The cyclic fatigue resistance of the instruments is shown in Table 4. Among the new instruments, regarding both the time and the number of cycles until fracture, PDL 35.05 had the highest resistance to fatigue, followed by SRF 35.04 and BTR 35.04, respectively ($P<0.05$). Among the used instruments, PDL and SRF presented higher time to fracture than did BTR ($P<0.05$). However, when the number of cycles was analyzed, PDL presented higher cyclic fatigue resistance than did SRF and BTR, respectively ($P<0.05$). The within-group comparison between new and used instruments showed that no instrument was significantly affected by clinical use ($P>0.05$).

Figures 1 and 2 show SEM images of BTR, SRF, and PDL, both new and used, after torsional and cyclic fatigue testing.

DISCUSSION

This study evaluated the quality of preparation of curved canals, torsional fatigue, and cyclic fatigue of new and used instruments of three rotary systems with different types of NiTi alloys. In view of the results obtained, the null hypothesis was partially rejected since there was a difference in torsional and cyclic fatigue resistance of the instruments, in addition to the fact that glide instruments were affected by simulated clinical use.

In the present study, single-rooted teeth with curvature between 15 and 30 degrees were used. Despite the difficulty in pairing samples of natural teeth, they were standardized in terms of degree of curvature by digital radiography and the baseline volume of both the entire canal and the apical third were standardized by micro-CT (Table 1).

Curved canals pose a great challenge during mechanical preparation since errors such as zipping, step, excessive wear, and instrument fractures can occur, worsening the prognosis of endodontic treatment [21,22]. In addition, there is still no consensus on the ideal diameter of apical preparation; however, several studies have demonstrated numerous benefits when this preparation is greater than a #25 instrument [23-25]. Therefore, in the present study, three rotary systems were used, in which the finishing instrument had a size 35. Probably, because of the standardization of the final diameter and close taper (BTR 0.04, SRF 0.04, and PDL 0.05), there was no significant difference among the groups regarding the percent volume increase ($P>0.05$), even knowing that the final instruments present different types of cross sections and NiTi alloys (BTR - triangular section and conventional NiTi, SRF - triangular convex section and NiTi Blue, PDL – S-shaped section and NiTi CM).

An important factor during the biomechanical preparation of curved canals is the maintenance of their path [12,22]. Therefore, we analyzed canal transportation and centering ability of the systems in the apical region (last 4 mm), which corresponds to the region of the curvature (Table 2). There were no significant differences among the groups ($P>0.05$) for any of the analyses. Regarding canal transportation, the three groups presented values close to 0, i.e., lower than 0.3, which is a threshold value with no negative impact on the prognosis of endodontic treatment [12]. Regarding centering ability, it is known that, according to the formula proposed by Gambill et al. [17], the closer to 1, the better the centering ability. Although no significant differences were noted, PDL obtained values closer to 1, followed by SRF and BTR, respectively. This can be mainly explained by the types of alloy used by the systems. PDL uses s CM alloy and SRF utilizes a Blue alloy. BTR has a conventional NiTi alloy, and several studies have demonstrated that heat-treated alloys have greater flexibility and better maintenance of the canal path than do conventional alloys [12,26,27].

Because these systems are relatively new in the market, few studies have analyzed quality of preparation. Most of these studies revealed similar results for the behavior of BTR to the ones found in the present study [8,9]. Pinheiro et al. (12) observed that, although there was no statistical difference, PDL has better centering ability than that observed in different heat-treated rotary systems, in line with the results of this study.

Another important factor during biomechanical preparation of curved canals is the creation of the glide path, since it can improve the quality of preparation and reduce the risk of fracture of shaping instruments [4,5,28,29]. Therefore, most rotary systems have a specific instrument for this role. Generally, glide path instruments show high variability in tip diameter, taper, cross-section, and type of NiTi alloy among systems. These factors can contribute to different behaviors of the instruments [4]. In the present study, glide path instruments were used in three teeth with curved canals and then subjected to torsional fatigue test, which analyzed maximum torque (N.cm) and maximum angular deflection (o). Concomitantly, the same instruments, although new, were also subjected to the same test using a previously validated methodology [7,29].

The analysis of maximum torque of the new and used instruments showed that SRF 15.04 presented higher values than did PDL 25.01 and BTR 10.06 ($P<0.05$). These findings can be explained by the fact that SRF has a quadrangular cross section and a larger tip diameter than does BTR, which has a triangular cross section, with a smaller amount of metal mass in initial millimeters. Moreover, although PDL and SRF both have a quadrangular cross section, PDL has a lower taper (0.01) and CM NiTi alloy, with lower torsional resistance [4,30]. One factor that could influence torsional stress is the rotational speed per minute (RPM); however, Ha et al. [31] demonstrated that it does not alter torsional fatigue. It should be emphasized that both SRF and PDL maintained the same mean maximum torque (0.4 and 0.2, respectively) after simulated clinical use, while in BTR it decreased from 0.2 to 0.1. The fact that torsional fatigue did not change in SRF and PDL after clinical use may be related to the heat treatment they both had. As BTR does not have heat treatment for its alloy, torsional fatigue resistance decreased, corroborating the findings of a previous study that analyzed instruments with conventional NiTi alloys [13].

Regarding angular deflection, both in the evaluation of new and used instruments, PDL 25.01 obtained significantly better results than did SRF 15.04 and BTR 10.06, respectively ($P<0.05$). This variable is directly related to the type of heat treatment of the instrument and to its taper, where the more flexible the instrument, the greater the angle of deflection [4,32]. There are no studies in the literature evaluating the torsional fatigue of BTR and SRF systems for comparison of the results obtained. Only one study evaluated PDL 25.01 and obtained results similar to those of the present study [4]. In addition, it should be noted that the angular deflection of the three instruments was affected by clinical use. This may have occurred because, in addition to torsional fatigue, the instruments used in the preparation of the curved canals were also subjected to cyclic fatigue, leading to a reduction in angular deflection.

After creating the glide path, the root canal is shaped by the instruments. When these instruments work in a curved canal, they suffer cyclic fatigue because of tensile and compressive forces at the maximum point of curvature [2,33]. In the present study, the new and used finishing instruments (size 35) were subjected to the cyclic fatigue test to verify their safety in canals with moderate curvature. In the analysis of the time necessary until fracture of the instruments, both new and used, PDL 35.05 demanded significantly longer time than did SRF 35.04 and BTR 35.04, respectively ($P<0.05$). The same results were also observed for the number of cycles, since this varies according to the speed used ($P<0.05$). The literature is very scarce when it comes to studies on the mechanical properties of the systems tested. de Menezes et al. [34] also obtained better behavior for PDL even when compared to heat-treated Gold instruments. These results might have been obtained due to the design of the instrument (S-shaped cross-section), but mainly to the heat treatment CM of PDL, which provides greater flexibility and resistance to cyclic fatigue [7,19,34]. As to the intermediate results obtained for SRF, which has a Blue heat treatment, an analogy can be made with the findings of Alcalde et al. [7] and Silva et al. [33], where the instrument with Blue heat treatment obtained good results but worse ones than those of the instrument with CM heat treatment. In relation to BTR, made of conventional NiTi alloy, several studies have shown that this type of alloy has less resistance to cyclic fatigue than do NiTi instruments with some type of heat treatment [35-37]. Another factor that could influence cyclic fatigue strength is the speed used for each instrument. However, a study revealed no influence of speed, considering the design of the instrument and the type of alloy it is made of to be the most important factors [35]. Note that none of the finishing instruments tested in the present study were significantly affected by clinical use. This may have occurred because the test was performed with the finishing instrument, which does not suffer as much stress as the first ones of the shaping.

CONCLUSIONS

Despite the limitations of this study, it can be concluded that BTR, SRF, and PDL rotary instruments were safe and presented similar quality in the shaping of canals with moderate curvature. However, different behaviors were observed in the mechanical properties of the instruments. In torsional fatigue, SRF 15.04 presented the highest torque values, PDL 25.01 presented the highest values of angular deflection, and BTR 10.06 was the most frequently affected by simulated clinical use. PDL 35.05 presented higher resistance to cyclic fatigue, followed by SRF 35.04, and the finishing instruments were not affected by simulated clinical use.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflicts of interest.

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Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee.

Informed consent For this type of study, formal consent is not required.

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FIGURE LEGENDS

Figure 1 - Scanning electron microscopy images of new (A, B, and C; G, H, and I; M, N, and O) and used (D, E, and F; J, K, and L; P, Q, and R) instruments of BT-Race, Sequence Rotary File, and ProDesign Logic systems, respectively, after torsional fatigue testing.

Figure 2 - Scanning electron microscopy images of new (A, C, and E) and used (B, D, and F) instruments of BT-Race, Sequence Rotary File, and ProDesign Logic systems, respectively, after cyclic fatigue testing.

Figure 1 Click here to access/download;Figure;Figure 1.jpg

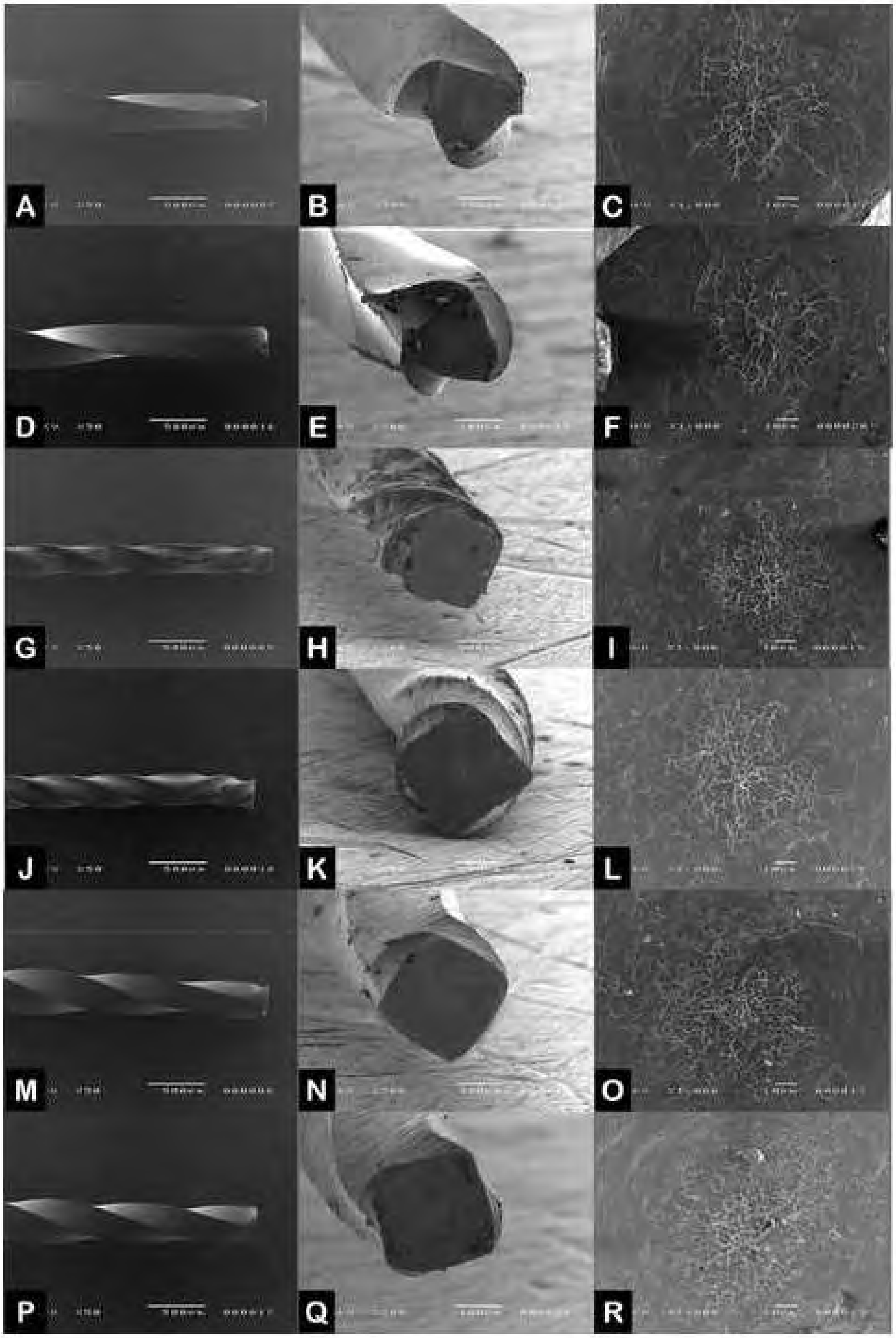

Figure 2

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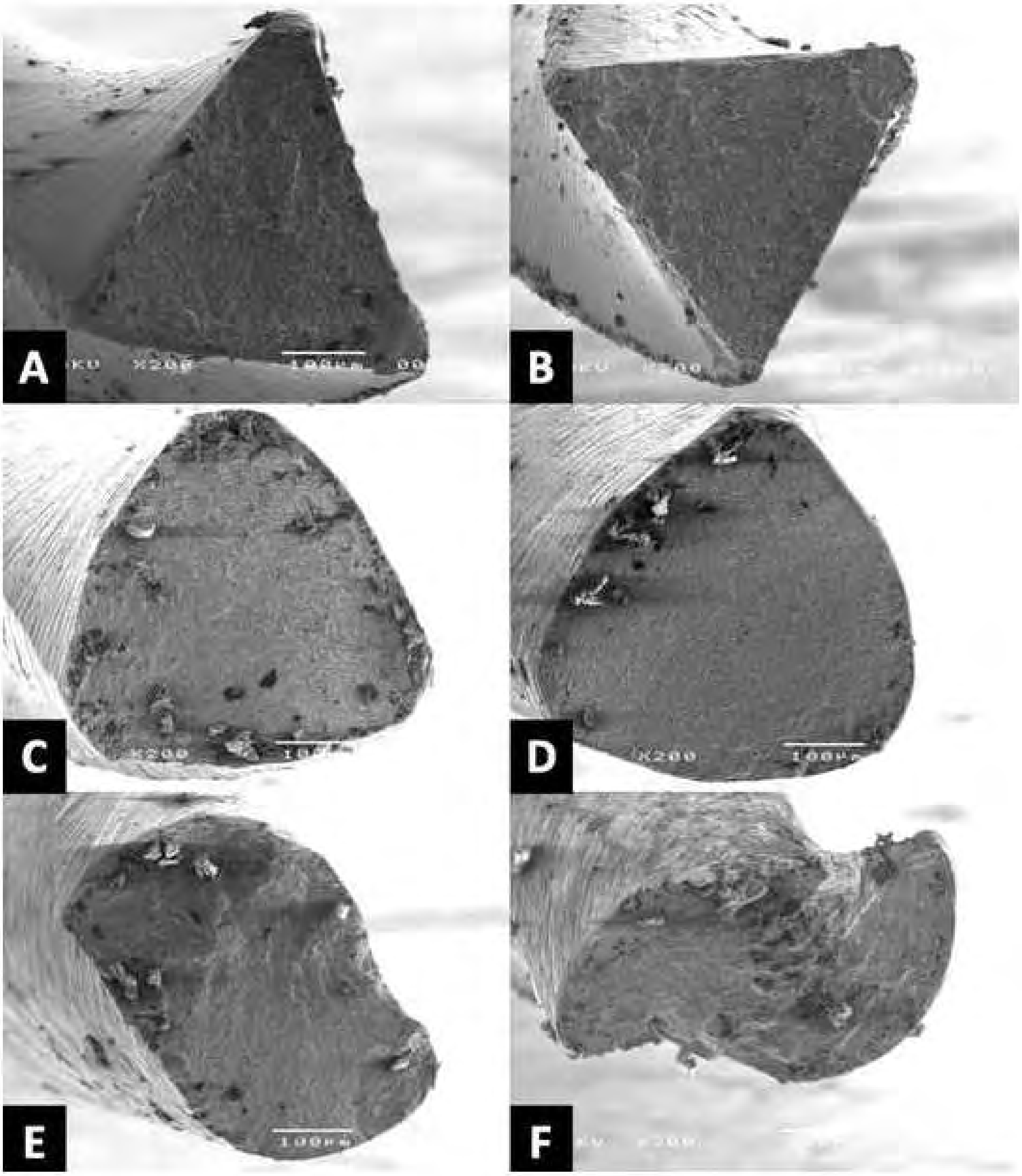

Table

Table 1. Median, minimum and maximum values of the volume, in mm3, and the percentage of volume increase after the use of the different rotary systems.

	Region	Initial volume (mm3)	Final volume (mm3)	% volume increase
BTR		0.19 (0.05/0.59)[aA]	0.34 (0.23/0.64)[B]	105.5 (18.0/370.0)[a]
SRF	APICAL	0.20 (0.12/0.57)[aA]	0.50 (0.24/0.72)[B]	107.4 (16.6/344.4)[a]
PDL		0.30 (0.18/0.42)[aA]	0.50 (0.35/0.64)[B]	63.55 (27.9/154.6)[a]
BTR		2.36 (1.05/4.22)[aA]	3.38 (2.27/4.78)[B]	46.0 (16.3/124.2)[a]
SRF	TOTAL	3.32 (1.09/5.84)[aA]	4.17 (3.02/6.48)[B]	39.6 (16.9/176.3)[a]
PDL		3.15 (1.33/4.51)[aA]	4.20 (3.59/4.84)[B]	29.35 (15.5/172.6)[a]

Different lowercase letters in the same column indicate significant difference among groups (P<0.05).
Different capital letters on the same line indicate intragroup signifcant difference (P <0.05).

Table 2. Mean, minimum and maximum values, in mm3, of the canal transportation and centering ability after the use of the different rotary systems.

	Canal transportation			Centering ability		
Region	BTR	SRF	PDL	BTR	SRF	PDL
1 mm	-0.09[a] (-0.37/0.19)	-0.03[a] (-0.17/0.25)	-0.01[a] (-0.07/0.06)	0.31[a] (0.01/0.98)	0.40[a] (0.02/1)	0.50[a] (0.09/1)
2 mm	-0.08[a] (-0.29/0.33)	-0.03[a] (-0.18/0.04)	-0.03[a] (-0.38/0.13)	0.14[a] (0.01/0.99)	0.44[a] (0.13/0.96)	0.51[a] (0.10/0.95)
3 mm	0.11[a] (-0.14/0.21)	0.08[a] (-0.25/0.17)	-0.04[a] (-0.11/0.03)	0.25[a] (0.01/0.98)	0.33[a] (0.05/0.93)	0.55[a] (0.16/1)
4 mm	-0.07[a] (-0.15/0.10)	-0.05[a] (-0.14/0.06)	0.02[a] (-0.05/0.13)	0.39[a] (0.01/0.97)	0.49[a] (0.07/0.95)	0.66[a] (0.11/1)

In the analysis of canal transportation, positive values indicate wear to the inner wall of the curvature and negative indicate wear to the outer wall of the curvature.
Different lowercase letters on the same line indicate significant difference among groups (P<0.05).

Table 3. Mean values of torque (N.cm), angle of rotation (°) of new instruments and after three uses.

Torsional strength								
Instruments	New instruments				Used instruments			
	Torque (N.cm)		Angle (°)		Torque (N.cm)		Angle (°)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
BTR 10.06	0.2^{aA}	0.04	363.4^{aA}	12.7	0.1^{aB}	0	303.1^{aB}	13.7
SRF 15.04	0.4^{bA}	0.09	462.1^{bA}	16.1	0.4^{bA}	0.06	367.2^{bB}	14.1
PDL 25.01	0.2^{aA}	0.04	952.7^{cA}	11.3	0.2^{cA}	0.03	810.9^{cB}	27.6

SD, standard deviation.

Different lowercase letters in the same column indicate statistical differences among groups ($P<0.05$).
Different capital letters on the same line indicate statistical differences between new and used instruments of the same group ($P<0.05$).

Table 4. Mean values of time (in seconds), number of cycles (NCF) of new instruments and after three uses.

Cyclic Fatigue								
Instruments	New instruments				Used instruments			
	Time (seconds)		Cycles (NCF)		Time (seconds)		Cycles (NCF)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
BTR 35.04	18.8^{aA}	4.2	250.6^{aA}	57.3	13.6^{aA}	13.7	181.3^{aA}	50.5
SRF 35.04	128.4^{bA}	8.1	1070.0^{bA}	67.9	126.8^{bA}	22.1	1056.6^{bA}	104.7
PDL 35.05	171.6^{cA}	13.4	2717.0^{cA}	171.1	164.9^{cA}	23.9	2610.9^{cA}	128.0

SD, standard deviation.

Different lowercase letters in the same column indicate statistical differences among groups ($P<0.05$).
Different capital letters on the same line indicate statistical differences between new and used instruments of the same group ($P<0.05$).

2.4 Article 4 - Evaluation of the quality in the retreatment and resistance to cyclic fatigue of mechanized systems with different thermal treatments

The article presented in this thesis was written according to the Journal of Endodontics instructions and guidelines for article submission

ABSTRACT

Objectives The aim of the present study was to compare the Reciproc, Reciproc Blue, Pro-R and ProDesign Logic RT systems for the ability to remove filling material in curved canals and cyclic fatigue, as well as to evaluate the influence of simulated clinical use on resistance cyclic fatigue. **Materials and methods** Sixty single-rooted tooth with oval shaped canal showing curvature between 20 and 35º were instrumented, filled and scanned in computerized microtomography. The teeth were then divided into 4 groups (n = 15) according to the systems used in endodontic retreatment: Reciproc 25.08 and 40.06, Reciproc Blue 25.08 and 40.06, Pro-R 25.08 and 40.06, ProDesign Logic RT 25.08 and 40.05. After retreatment, the teeth were again scanned and analyzed for the volume of total remaining filling material and also in the apical region. During the retreatment, one instrument was used per tooth and the working time of the size 25 instruments to reach the working length was measured. These same instruments were later submitted to the cyclic fatigue test. Fifteen new instruments and instruments used in endodontic retreatment (n = 15) were submitted to the test. The data were submitted to statistical analysis with significance level of 5%. **Results** None of the groups completely removed the filling material, however, all of them significantly decreased the volume after the retreatment until the instrument size 40 ($P<0.05$). In the apical region there were no significant differences among the groups in the volume of remaining filling material ($P>0.05$), however, in total, ProDesign Logic RT significantly decreased volume more than Reciproc Blue and Pro-R ($P<0.05$) and without difference for Reciproc ($P>0.05$). ProDesign Logic RT was significantly faster than the other instruments ($P<0.05$). Regarding the time of the cyclic fatigue, Reciproc Blue presented greater resistance than the other groups, both for new instruments and after clinical use ($P<0.05$). However, in the analysis of the number of cycles Reciproc Blue did not present a significant difference for ProDesign Logic RT ($P>0.05$) and both were more resistant to cyclic fatigue than Reciproc and Pro-R ($P<0.05$), both for new instruments and after clinical use. The simulated clinical use did not influence the cyclical fatigue of any instrument ($P>0.05$). **Conclusions** ProDesign Logic RT presented lower volume of remaining filling material and was significantly faster in endodontic retreatment. Reciproc Blue and ProDesign Logic RT showed greater resistance to cyclic fatigue. The simulated clinical use did not affect the resistance of the instruments.

Keywords: Endodontic, microcomputed tomography, retreatment, cyclic fatigue.

INTRODUCTION

Recently, several rotary and reciprocating mechanized systems have been introduced in the market with different types of heat treatment, which have excellent flexibility and fracture resistance, and are able to shape curved canals adequately (1-2). However, even with a correct shaping and after adequate root canal filling, failures can occur requiring the need for endodontic retreatment (3-4).

The purpose of retreatment is to remove the largest possible quantity of filling material to gain access to apical and then carry out a suitable cleaning of the root canal system in order to promote canal sealing (5-6). During the removal of the filling material from the canal, the instrument used must have good mechanical properties, since it undergoes great fatigue during this stage, in order to avoid accidents occurring, making it difficult to clean the root canal (1,7). In cases of curved canals, in addition to the difficult removal of the filling material, the instrument suffers further stress due to cyclic fatigue leading to an increased risk of fracture (1).

Several instruments with new technologies were developed with the aim of making the mechanized instruments efficient in the removal of filling material and safe in curvatures (1,6,8). It was proposed the use of reciprocating instruments which have been reported to present greater resistance to cyclic fatigue (6-7,9). Reciproc (VDW GmbH, Munich, Germany) was one of the first reciprocating systems to be used in root canal shaping, however, several studies have also demonstrated its efficiency in endodontic retreatment (5,10). In order to further improve the mechanical properties, the Reciproc suffered a process of heating/cooling giving rise instruments Reciproc Blue (VDW GmbH, Munich, Germany) which have a NiTi alloy with blue technology (5,11). These instruments have been the subject of studies that point to a greater resistance to cyclic fatigue than their predecessor (12-13) and also show to be efficient in endodontic retreatment (5,11). Both Reciproc and Reciproc Blue are composed of 3 instruments: 25.08, 40.06 and 50.05.

Subsequently, several specific systems for endodontic retreatment were inserted in the market. Among them, the Pro-R reciprocating system (MK Life Medical and Dental Products, Porto Alegre, Brazil) is composed of instruments 25.08, 40.06 and 50.05 and the ProDesign Logic RT rotary system (Easy Dental Equipment, Belo Horizonte, Brazil) which has instruments 30.10, 25.08 and 20.06. These systems present different designs and heat treatment in the NiTi alloy in order to provide a good filling removal capacity and to be able to maintain the curved canal trajectory with the minimum risk of fracture, however, there are no studies yet who evaluated these systems.

Therefore, the objective of this study was to compare the Reciproc, Reciproc Blue, Pro-R and ProDesign Logic RT systems for the ability to remove filling material in curved canals and the resistance to cyclic fatigue, as well as to evaluate the influence of the simulated clinical use in resistance to cyclic fatigue of instruments size 25 and .08 taper. The null hypotheses are: (a) There is no difference in the ability to remove filling material among systems, (b) there is no difference in resistance to cyclic fatigue among instruments, and (c) there is no influence of simulated clinical use on resistance to cyclic fatigue.

METHODS

The present study was approved by the Human Research Ethics Committee (process number: 88418518.4.0000.5417).

Tooth preparation

Sixty single-rooted tooth with oval shaped canal with the curvature of 20 to 35 ° according to the method of Schneider (14) were used. The canals were shaped with the ProDesign Logic (Easy Dental Equipment, Belo Horizonte, Brazil) rotating system where the last instrument of the sequence was size 35 and .05 taper. A final irrigation protocol with sodium hypochlorite and 17% EDTA was performed, and then the canals were dried with size 35 absorbent paper cones. The canals were filled with gutta-percha and endodontic cement AH Plus (Dentsply Maillefer, Ballaigues, Switzerland), by the hybrid technique of Tagger. After filling the teeth were stored in an oven at 37ºC at 100% relative humidity for 30 days. After this time, the teeth were scanned in micro-CT using predefined parameters and divided into 4 groups (n = 15) according to the system used in the retreatment:

Group 1: Reciproc - In order to facilitate the penetration of the instrument in gutta-percha, 0.1 mL of solvent (xylol) was inserted at the entrance of the canal for 1 minute. The Reciproc 25.08 instrument was used to remove the filling material in the “Reciproc all” function on the endodontic electric motor (VDW GmbH, Munich, Germany) until the instrument reached working length, set 1 mm below the foramen apical. Each time the instrument was removed from within the canal it was cleaned with a gauze to remove the adhered filling material. Subsequently, the Reciproc 40.06 instrument was used in the same way as the first.

Group 2: Reciproc Blue - It was performed similarly to group 1, but using the instrument Reciproc Blue 25.08 and complemented with the instrument Reciproc Blue 40.06.

Group 3: Pro-R - Was performed in a similar way to groups 1 and 2, but using instrument Pro-R 25.08 and complemented with instrument Pro-R 40.06.

Group 4: ProDesign Logic RT - It was done in a similar way to the other groups, but using the ProDesign Logic RT 25.08 instrument in the rotary function at a speed of 900 RPM and 4N of torque in the Easy Endo SI endodontic electric motor (Easy Dental Equipment, Belo Horizonte, MG, Brazil) and complemented by the ProDesign Logic 40.05 instrument.

In all groups, a movement with slight apical pressure was performed, with a range of 2 to 3 mm. Irrigation of the root canals was done with 3mL of 2.5% sodium hypochlorite each time the instrument was removed from the canal and final irrigation with 5mL of the same solution. The canals were then irrigated with 17% EDTA for 3 minutes and washed with 5mL of saline solution. The canals were dried with absorbent paper cones and scanned in micro-CT using the same initial parameters.

Micro-CT procedures

A 0.5-mm aluminum filter, 50 kV, 800 μA, voxel size of 19.6 μm, rotation angle of 0.7, and total rotation of 360º were used as scanning parameters, producing images with a resolution of 1304 x 1024 pixels. Each scan resulted in images that were reconstructed using NRecon software v1.6.4.8 (Bruker-micro-CT). A silicone mold was made for each tooth to ensure scanning in the same position so as not to interfere in the subsequent analysis.

Remaining filling material volume

The images obtained after root canal filled and the retreatment stage were reconstructed in the NRecon v1.6.4.8 program and overlaid using a 3D function of the DataViewer v.1.5.1 (Bruker micro-CT) software. The CTAN v.1.12 (Bruker micro-CT) software was then used to measure the volume (mm 3) of filling material of the apical region, which comprises the last 4 mm, and the total volume, which comprises the last 10 mm of the root canal. The volume of filling material remaining after the retreatment procedure was expressed as a percentage.

Working time

The time required to remove the filling material was measured by means of a digital timer. Time was measured only when the instrument was in action within the root canal. The working time was that necessary until the instrument of size 25 reached the working length.

Cyclic fatigue test

For the cyclic fatigue test only the instruments of size 25 and .08 taper were used, because they are the instruments that suffer the most fatigue during the retreatment. The methodology used for this test was based on that described by Marks Duarte et al (15). However, an angulation of 30 ° and radius of 5mm was used. New instruments (n = 15) of each system and after use in retreatment (n = 15) were used in the test. The time (in seconds) needed until the instrument fractured was measured using a digital timer. In order to verify the exact time, a video recording was performed during this step. Then, based on the time and speed used by each system, the number of cycles required for the fracture of the instrument was calculated.

Scanning electron microscopy

After the cyclic fatigue test, the fractured surface of the new and used instruments were examined by scanning electron microscope (JSM-TLLOA; JEOL, Tokyo, Japan) at 250x magnification, to evaluate the topographic characteristics.

Statistical analysis

The statistical analysis was performed using GraphPad Prism 5 software (La Jolla, CA, USA). The data were subjected to D'Agostino-Pearson test to verify if there was a normal distribution. For analysis of the volume of filling material, the non-parametric Kruskal-Wallis and Dunn tests were used for comparison among the groups and the Wilcoxcon test for intragroup analysis. For analysis of the resistance to cyclic fatigue and instrument retreatment time, the ANOVA and Tukey parametric tests were used for comparison among groups and unpaired t-test for intragroup comparison. The level of significance was 5%.

RESULTS

The median, minimum and maximum values of the initial, final volume and percentage of remaining filling material are shown in table 1. It can be observed that in relation to the initial volume, in both the apical and total regions, there were no significant differences among the groups indicating a correct sample pairing ($P>0.05$). In relation to the percentage of total remaining material after retreatment, it was observed that ProDesign Logic RT removed significantly more filling material than Reciproc Blue and Pro-R ($P<0.05$) and Reciproc did not present difference with any group ($P>0.05$). In the apical region there were no significant differences among the systems ($P>0.05$). In the intragroup analysis it was observed that, in all the systems, there was a significant reduction in the filling material volume ($P<0.05$).

The values of the mean and standard deviation of the cyclic fatigue strength of both new instruments and after simulated clinical use, as well as the working time of the instrument size 25 and .08 taper during the retreatment are represented in table 2. In relation to working time, ProDesign Logic RT was significantly faster than the other groups ($P<0.05$). In relation to the resistance to cyclic fatigue, both new and used instruments, Reciproc Blue presented the most time necessary until the instrument fractured in relation to Reciproc, Pro-R and ProDesign Logic RT ($P<0.05$). However, when analyzing the number of cycles, Reciproc Blue and ProDesign Logic RT presented greater resistance to cyclic fatigue than Reciproc and Pro-R ($P<0.05$), both for new instruments and after use. In the intragroup analysis, it was observed that there was no significant reduction in cyclic fatigue after simulated clinical use in any of the groups ($P>0.05$).

Figure 1 represents computerized microtomography images before and after the retreatment procedure.

Figure 2 shows scanning electron microscopy images of the instruments after the cyclic fatigue test.

DISCUSSION

The objective of this study was to evaluate the ability of different mechanized systems (Reciproc, Reciproc Blue, Pro-R and ProDesign Logic RT) in the ability to remove filling material in canals with moderate curvature, besides, to evaluate the resistance to cyclic fatigue of instruments size 25 and taper .08 and if simulated clinical use influences in the cyclic fatigue.

Several studies have been conducted to evaluate different removal procedure techniques of the root canal and all are unanimous that no method is able to completely filling material remove (5,8,11). These results corroborate with the data obtained in the present study in which, regardless of the kinematics and characteristics of the instruments used, all presented residual filling material (Table 1).

For this study, curved single-rooted tooth with oval shaped canal were used, which were shaped and subsequently filled. The groups were divided according to the degree of curvature and the volume of total and apical filling material. Table 1 shows that there were no significant differences among the systems regarding the volume of initial, total and apical filling material, indicating a correct sample pairing ($P>0.05$). In addition, in the same table, it is possible to notice that, in both evaluated regions, all the systems significantly decreased the amount of filling material after the retreatment procedures where instruments of size 25 were used and complemented with instruments of size 40 ($P<0.05$). These results corroborate with other studies that point out the need to use an additional large instrument to improve the removal of filling material in order to achieve a better cleaning of root canal systems (5,16-17).

Regarding the comparison among the groups regarding the volume of remaining filling material, it can be observed in Table 1 that, in the apical region, there were no significant differences among groups, however, in total, ProDesign Logic RT group remained significantly less material of Reciproc Blue and Pro-R groups ($P<0.05$) and with no difference for Reciproc ($P>0.05$). Thus, the null hypothesis (a) was rejected. The literature is controversial when comparing the filling removal capacity using reciprocating and rotational kinematics.

Studies have shown a better performance with reciprocating instruments (18-19), rotary (20-21) and both presenting similar results (6,22). A possible explanation for the results found in the present study may be related to the design of the instruments. While Reciproc, Reciproc Blue and Pro-R reciprocating instruments have an S-shaped cross-section, ProDesign Logic RT 25.08 has a triple helix section. In addition, Reciproc and Reciproc Blue present variable taper, decreasing as it goes towards the cervical while the ProDesign Logic RT system has fixed taper. These characteristics make the ProDesign Logic RT instruments have a greater volume of metallic mass and consequently there may be a greater contact of the instruments in the walls of the root canal removing a larger volume of filling material. Another factor that may have influenced the results is the continuous rotation kinematics used in ProDesign Logic RT which has the tendency to displace debris in the coronal region, while the reciprocating kinematics there is a controversy of what actually occurs, and some studies state that there is a greater displacement apically (20).

The ProDesign Logic RT instrument was significantly faster than Reciproc, Reciproc Blue and Pro-R ($P<0.05$), with respect to the working time of the size 25 instrument to reach working length (Table 2). This result seems to be directly related to the kinematic/velocity combination and the number of instruments used. The rotational kinematics have a screwing effect, which the reciprocating kinematics does not have, which favors the penetration of the instrument into the filling material (20). Along with this, ProDesign Logic RT used 3x higher speed also contributed to this instrument penetrating more easily and achieving significantly faster working length. Studies in the literature comparing different kinematics uses rotational systems that present more than one instrument in the technique and are used at lower speeds while reciprocating systems are unique instruments (6,19,23). These variations may lead to results different from those found in the present study where the rotational system used had only a single instrument and at a speed of 900 RPM.

For the analysis of resistance to cyclic fatigue of the instruments, a methodology already widely used by several authors was used (15,24). For this, a static model was used which reduces the variations that may occur during this analysis. One of the objectives of this study was to verify the resistance to cyclic fatigue of 4 instruments of size 25 and .08 taper presenting different types of thermal treatment and design in two different situations: new instruments, without any use, and after the use in the endodontic retreatment of a curved single-rooted tooth with oval shaped canal. The results showed that there were significant differences among the instruments in both situations, thus rejecting the null hypothesis (b). The results showed a better performance of the heat-treated instruments with controly memory (CM) technology (Reciproc Blue and ProDesign Logic RT), corroborating with several other studies (12,25). Initially, the time required until the instrument fracture showed

Reciproc Blue with more resistance than Reciproc, Pro-R and ProDesign Logic RT ($P<0.05$), however, when the number of cycles was analyzed, which takes into account the speed used for each system, ProDesign Logic RT also showed significantly higher cyclic fatigue resistance than Reciproc and Pro-R ($P<0.05$), with no difference for Reciproc Blue ($P>0.05$). The results were similar for both new instruments and after simulated clinical use. Although ProDesign Logic RT exhibits the same type of heat treatment as the ProDesign R instrument (Easy Dental Equipment, Belo Horizonte, Brazil), a reciprocating instrument for canal shaping in which some studies showed greater resistance to cyclic fatigue than the Reciproc Blue (26-27), other factors interfered so that the results found were not similar. ProDesign Logic RT is a rotating instrument where the literature has shown to have lower resistance to cyclic fatigue than reciprocating instruments (9,28) and also have a triple-helix cross-section while ProDesign R presents a cross-section in S. This shows that the type of heat treatment is not the only one that influences the mechanical properties of the instrument, but other factors such as kinematics and design affect directly.

Regarding the Reciproc and Pro-R instruments, both have M-Wire thermal treatment NiTi alloy and similar design, where the difference between them is basically the Reciproc variable taper while the Pro-R presents fixed taper. Because this variation was almost imperceptible, the results of the cyclic fatigue resistance of both were very close and without significant difference ($P>0.05$). However, both showed less cyclical fatigue resistance than Reciproc Blue and ProDesgin Logic RT ($P<0.05$). There are no papers in the literature evaluating Pro-R and ProDesign Logic RT for results to be confronted. The best performance of Reciproc Blue on Reciproc corroborates with other studies which point out that it is directly related to the heat treatment with Blue technology of Reciproc Blue since both instruments have identical design (12-13). Although ProDesign Logic RT has a fixed taper and a triple helix cross section, thus presenting a greater volume of metal mass than the other instruments (Reciproc and Reciproc Blue - S-section and variable taper, Pro-R - section in S and fixed taper), it presented a significantly higher number of cycles than the M-Wire heat treatment instruments (Reciproc and Pro-R) for both new instruments and after clinical use. Thus, the thermal treatment with CM technology of ProDesign Logic RT must have been the great differential for the results found, since this technology is known for its great flexibility and resistance to cyclic fatigue (26-27,29).

The influence of simulated clinical use was also an objective of the present study. However, the results pointed out that none of the systems tested were affected by the use in endodontic retreatment of a single-rooted tooth with oval canal with the curvature. Thus, the last null hypothesis (c) was confirmed. There are no studies in the literature evaluating the effect of the simulated clinical use on the mechanical properties of the instruments.

Although moderate curvature canals were used in the present study, the fact that clinical use did not influence cyclic fatigue may be related to the fact that single canal teeth were used. Therefore, other studies should be conducted using teeth with more than one canal to observe whether simulated clinical use affects the resistance to cyclic fatigue of instruments in situations of greater complexity.

CONCLUSIONS

Under the conditions found, ProDesign Logic RT had the least volume of remaining filling material and required a shorter time to reach working length. Reciproc Blue and ProDesign Logic RT showed greater resistance to cyclic fatigue. Simulated clinical use did not affect any of the instruments.

Conflict of interest The authors declare that they have no conflicts of interest.

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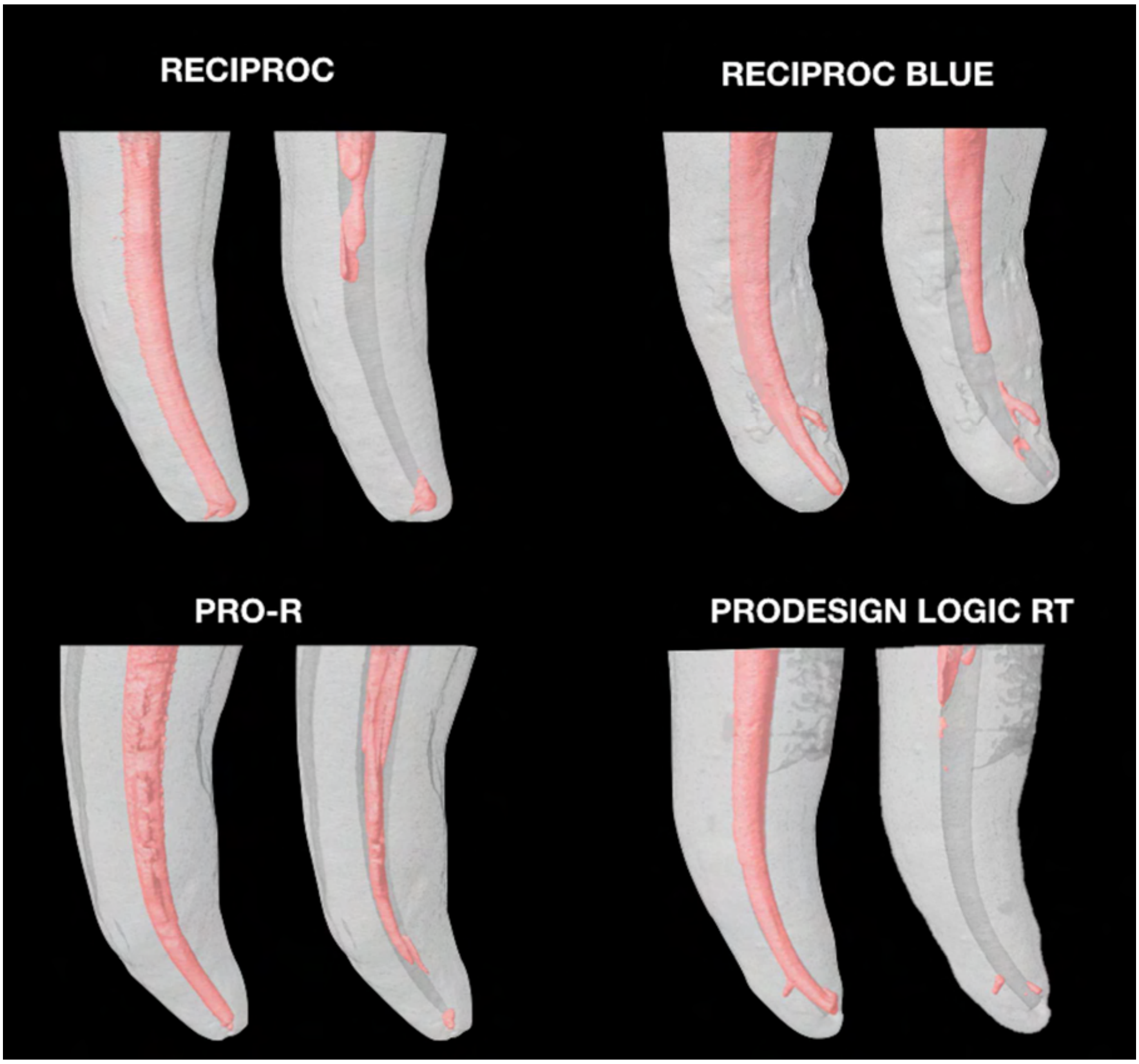
RECIPROC
RECIPROC BLUE
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PRODESIGN LOGIC RT

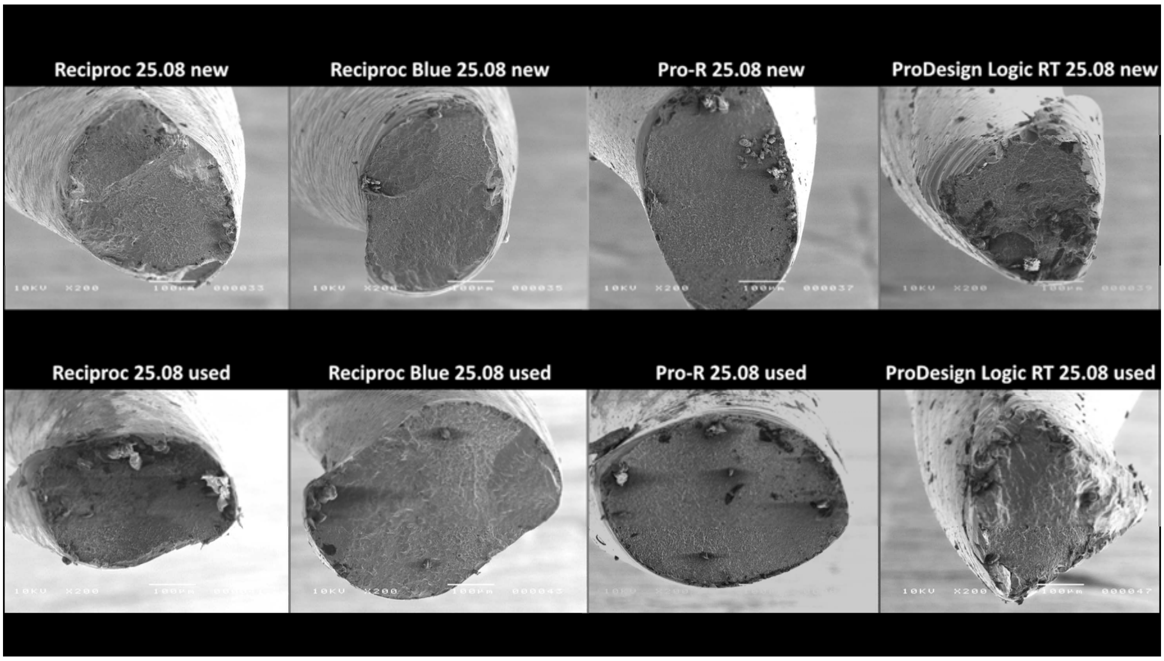
Reciproc 25.08 new
Reciproc Blue 25.08 new
Pro-R 25.08 new
ProDesign Logic RT 25.08 new
Reciproc 25.08 used
Reciproc Blue 25.08 used
Pro-R 25.08 used
ProDesign Logic RT 25.08 used

Table 1. Median, minimum and maximum values of the initial volume in mm3 and the percentage of filling material remaining after the use of the different instruments.

Instruments	Regions	Initial volume (mm3)	Final volume (mm3)	% of remaining filling material
RECIPROC	TOTAL	5.62 (3.6-9.7)[aA]	1.34 (0.1-4.3)[B]	27.21 (0.12-50.70)[ab]
RECIPROC BLUE	TOTAL	5.21 (3.5-10.1)[aA]	1.62 (0.1-6.1)[B]	35.68 (0.28-53.89)[b]
PRO-R	TOTAL	5.05 (3.3-9.2)[aA]	2.06 (0.2-7.7)[B]	42.08 (0.66-59.78)[b]
PRODESIGN LOGIC RT	TOTAL	5.13 (3.2-8.8)[aA]	0.34 (0.1-3.1)[B]	15.31 (0.12-39.54)[a]
RECIPROC	APICAL	1.07 (0.6-2.0)[aA]	0.09 (0-1.1)[B]	9.51 (0.43-59.32)[a]
RECIPROC BLUE	APICAL	1.08 (0.8-1.8)[aA]	0.15 (0-1.3)[B]	11.43 (0.1-65.8)[a]
PRO-R	APICAL	0.96 (0.6-1.9)[aA]	0.03 (0-0.9)[B]	4.07 (0.1-57.3)[a]
PRODESIGN LOGIC RT	APICAL	0.99 (0.7-1.4)[aA]	0.03 (0-0.6)[B]	3.45 (0.1-49.1)[a]

Different lowercase letters in the same column indicate significant difference among groups (P<0.05).
Different capital letters on the same line indicate significant difference among the same group (P<0.05).

Table 2. Mean values of time (in seconds), number of cycles (NCF) of new instruments and after three uses; and working time required to reach the working length during retreatment.

	CYCLIC FATIGUE								WORKING TIME	
Instruments	New instruments				Used instruments					
	Time (seconds)		Cycles (NCF)		Time (seconds)		Cycles (NCF)			
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
RECIPROC 25.08	266.1^{aA}	25.6	1330.5^{bA}	128.1	206.8^{aA}	25.6	1034.0^{bA}	128.2	88.47^{b}	30.9
RECIPROC BLUE 25.08	725.6^{bA}	78.4	3628.0^{aA}	292.2	670.1^{bA}	45.1	3350.5^{aA}	225.5	93.50^{b}	24.8
PRO-R 25.08	215.4^{aA}	90.3	1077.0^{bA}	251.8	210.1^{aA}	29.6	1050.5^{bA}	198.3	127.50^{b}	29.2
PRODESIGN LOGIC RT 25.08	225.6^{aA}	15.3	3384.0^{aA}	99.8	206.2^{aA}	33.5	3093.0^{aA}	103.6	23.36^{a}	19.4

SD, standard deviation.
Different lowercase letters in the same column indicate significant differences among groups ($P<0.05$).
Different capital letters on the same line indicate significant differences between new and used instruments of the same group ($P<0.05$).

2.5 Article 5 - Efficiency of ultrasonic, sonic and mechanical complementary cleaning methods in the removal of filling material remaining in curved canals

The article presented in this thesis was written according to the International Endodontic Journal instructions and guidelines for article submission

ABSTRACT

Objectives Compare efficacy in removing filling material remaining in curved canals using different complementary cleaning methods.

Materials and methods Sixty single-rooted tooth with oval shaped canal with curvature were prepared up to size 35 and .05 taper, filled and subsequently retreated. The teeth were then scanned in microCT and divided into 6 groups (n = 10) according to the complementary cleaning method: CUI with Irrisafe, CUI with NiTiSonic, PUI with Irrisafe, PUI with NiTiSonic, Eddy and XP-endo Finisher R. After, the teeth were again scanned in microCT. The volume of the filling material remaining before and after the application of the complementary methods was calculated and then calculated the percentage of material removed total and in the apical region. Data were submitted to the Kruskal-Wallis and Dunn tests with a significance level of 5%.

Results No complementary cleaning method completely removed the filling material, however, all significantly reduced the volume, both in the apical region and in the total root canal ($P<0.05$). There was no significant difference among the groups tested, regardless of the region analyzed ($P>0.05$).

Conclusions No method was effective in completely removing the remaining filling material. All complementary cleaning methods significantly reduce the volume of material, with no difference among them.

Keywords: Endodontic, microcomputed tomography, retreatment, root canal irrigation.

INTRODUCTION

During endodontic retreatment it is desirable that all filling material be removed to perform a adequate cleaning of the root canal system and thereafter a good filling. However, this is still a challenge since the work has shown difficulty in the complete removal of the filling material, especially in more complex cases such as curved canals (Rosa *et al.* 2015, Rodrigues *et al.* 2017). Several complementary cleaning methods have been proposed with the aim of enhancing the removal of filling material and the cleaning of root canals (Duque *et al.* 2017, Rodrigues *et al.* 2017, Bueno *et al.* 2019).

Ultrasound-activated irrigation (UAI), which consists of the activation of the irrigation solution using a specific instrument that induces acoustic streaming and cavitation, has been a proposed method to improve the cleaning of root canal system after treatment and endodontic retreatment (Cavenago *et al.* 2014, Duque *et al.* 2017, De-Deus *et al.* 2019). There are different types of ultrasonic tips to be used during this step as a non-cutting size 25 file (Irrisafe, Satelec Acteon, Mérignac, France) and nickel-titanium (NiTi) ultrasonic tips (NiTiSonic, Ultradent Products Inc, South Jordan, Utah), the latter being made especially for curved canals due to their flexibility (Bueno *et al.* 2019, Swimberghe *et al.* 2019).

In addition to the different types of instruments that can be used coupled to an ultrasound unit, the UAI can be performed intermittently (passive ultrasonic irrigation - PUI) and continuous (continuous ultrasonic irrigation - CUI) (Rodrigues *et al.* 2017, Chan *et al.* 2019). However, the literature is controversial as to the real benefits of UAI, both in treatment and in endodontic retreatment, where some authors affirm that there is a significant improvement in cleaning and/or removal of filling material (Rodrigues *et al.* 2007; Silveira *et al.* 2018, Borges *et al.* 2019, Bueno *et al.* 2019) while others claim to have no difference (Fruchi *et al.* 2014, Rosa *et al.* 2015, Chan *et al.* 2019).

Thus, other complementary cleaning methods have recently been manufactured and incorporated in the market in order to enhance the cleaning of the root canal system. Eddy (VDW, Munich, Germany) is a polymer tip that is activated by sonic vibrations by a conventional air scaler operating at a frequency of 6000 Hz (Zeng *et al.* 2018, Donnermeyer *et al.* 2019). Studies have shown encouraging results where Eddy has been shown to be effective in biofilm and smear layer removal, and has improved the dissolution of organic tissue and removal of filling material during retreatment (Conde *et al.* 2017, Urban *et al.* 2017, Donnermeyer *et al.* 2019, Kaloustian *et al.* 2019a, Swimberghe *et al.* 2019).

In addition, the XP-endo Finisher R instrument (FKG Dentaire, La Chaux-de-Fonds, Switzerland) was specifically developed to be used to improve cleaning during endodontic retreatment (Campello *et al.* 2019, Machado *et al.* 2019). This instrument has size 30 and taper zero, and is manufactured with a specific NiTi alloy named MaxWire (Martensite- Austenite ElectropolishFleX). This alloy allows the instrument to expand at body temperature improving its range (Campello *et al.* 2019, De-Deus *et al.* 2019).

As in the literature there is still no consensus on the best method to improve cleaning during retreatment and taking into account the necessity and difficulty of removing remaining filling material during retreatment, especially in complex anatomies, the objective of the present study was to compare the effectiveness in removing filling material in curved canals from the following complementary cleaning methods: CUI with Irrisafe, CUI with NiTiSonic, PUI with Irrisafe, PUI with NiTiSonic, Eddy and XP-endo Finisher R. The null hypotheses tested were:

I - Complementary cleaning methods do not improve the removal of remaining filling material in curved canals;

II - There is no difference among the complementary cleaning methods in the ability to remove filling material remaining in curved canals.

METHODS

The present study was approved by the Human Research Ethics Committee (process number: 88418518.4.0000.5417).

Tooth preparation

Sixty single-rooted tooth with oval shaped canal with the curvature of 20 to 35 ° according to the method of Schneider (1971) were used. The teeth were shaped with final size 35 and .05 taper with ProDesign Logic rotary system (Easy Dental Equipment, Belo Horizonte, Brazil). Final irrigation protocol with sodium hypochlorite and 17% EDTA was performed, and the canals were then dried with a size 35 absorbent paper coen. The canals were filled with gutta-percha and endodontic cement AH Plus (Dentsply Maillefer, Ballaigues, Switzerland) by the Tagger hybrid technique. After filling the teeth were stored in an oven at 37ºC at 100% relative humidity for 30 days. The teeth were then submitted to endodontic retreatment with instrument size 40 and .06 taper. Subsequently, the canals were irrigated with 10 mL of saline solution using syringe and 30-gauge needle (NaviTip, Ultradent, South Jordan, UT) for 1 minute and scanned in computerized microtomography (micro-CT) using predefined parameters. Then, the teeth were divided into 6 groups (n = 10) according to the complementary cleaning method:

Group 1: Continuous Ultrasonic Irrigation (CUI) with Irrisafe - Ultrasonic agitation was performed for 1 minute while irrigation with saline solution was performed concomitantly with agitation. For this, an insert Irrisafe 20.00 tip (Satelec Acteon, Mérignac, France) was used by an ultrasonic device (P5 Newton; Satelec Acteon, France) at power 7. The insert was positioned centrally in the root canal 1 mm before the working length.

Group 2: Continuous Ultrasonic Irrigation (CUI) with NiTiSonic - Procedure similar to the previous one was performed, however the NiTiSonic 20.02 tip insert (Ultradent Products Inc., South Jordan, USA) was used.

Group 3: Passive Ultrasonic Irrigation (PUI) with Irrisafe - 2 ml of saline solution was inserted into the canal and the Irrisafe insert was positioned 1 mm before working length and shaken for 20 seconds. Then, a similar procedure was performed 2 times more. For this, the insert Irrisafe 20.00 tip (Satelec Acteon) was driven by an ultrasonic device (P5 Newton; Satelec) at power 7.

Group 4: Passive Ultrasonic Irrigation (PUI) with NiTiSonic - The procedure was similar to Group 3, but agitation was performed using the NiTiSonic 20.02 tip insert (Ultradent Products Inc).

Group 5: Eddy - Similar procedure to groups 3 and 4 was performed, however the activation was performed with the instrument Eddy 25.04 (VDW) coupled to a sonic device (Sonic Borden 2000N KaVo Kerr, Joinville, SC, Brazil). Movements were made up and down over a distance of 4 mm, starting 1 mm before the working length according to the manufacturer's recommendations.

Group 6: XP-endo Finisher R - Procedure similar to the previous 3 was performed, however the XP-endo Finisher R 30.00 instrument (FKG, La Chaux-de-Fonds, Switzerland) was used in an endodontic motor (VDW, Munich, Germany) with a speed of 1000 RPM and 1 Ncm of torque making slow and smooth movement of 7-8 mm, starting 1 mm before the working length.

At the end, the canals were irrigated with 4 ml of saline solution. All these procedures were performed with the roots in contact with water at 37° C using a heater (Hopar Aquarium Heater H-606, Aquatica Brazil Com. Ltda, Brazil) and monitored by a thermometer (Aquarium Thermometer ADT-01F, Jin Li Jia Electromechanical Limited Company, China). The canals were then dried with absorbent paper cones selected according to the final instrument size and scanned again into the micro-CT, with the same previous scanning parameters.

Micro-CT procedures

A 0.5-mm aluminum filter, 50 kV, 800 µA, voxel size of 19.6 µm, rotation angle of 0.6, and total rotation of 360º were used as scanning parameters, producing images with a resolution of 1304 x 1024 pixels. The images were reconstructed using NRecon software v1.6.4.8 (Bruker-micro-CT). A silicone mold was made for each tooth to ensure scanning in the same position so as not to interfere in the subsequent analysis.

Volume of filling material removed

The images obtained after retreatment and the complementary cleaning step were reconstructed in the NRecon v1.6.4.8 program and overlaid using a 3D function of the DataViewer v.1.5.1 (Bruker micro-CT) software. The CTAN v.1.12 (Bruker micro-CT) software was then used to measure the volume (mm 3) of filling material of the apical region, which comprises the last 4 mm, and the total volume, which comprises the last 10 mm of the canal. The volume of filing material removed after the complementary cleaning methods was calculated and expressed as a percentage.

Statistical analysis

The statistical analysis was performed using GraphPad Prism 5 software (La Jolla, CA, USA). The data were subjected to D'Agostino-Pearson test to verify if there was a normal distribution. Kruskal-Wallis and Dunn non-parametric tests were used for comparison among the groups and the Wilcoxcon test for intragroup analysis. The level of significance was 5%.

RESULTS

The median, minimum and maximum values of the remaining filling material volume and percentage of removal promoted by the complementary cleaning methods are shown in Table 1. It can be observed that, in the apical and total regions, there was no significant difference among the groups in relation to the volume of filling material remaining before the application of the complementary cleaning method, showing a correct sample pairing ($P>0.05$). Regarding the percentage of filling material removed by the complementary methods, it was observed that there was no difference among the groups ($P>0.05$).

In the intra-group analysis, it was observed that, independently of the analyzed region, all the complementary cleaning methods significantly reduced the volume of remaining filling material ($P<0.05$).

Figure 1 represents computerized microtomography images after retreatment and after the use of complementary cleaning methods.

DISCUSSION

The objective of the present study was to evaluate and compare the efficacy of six different complementary cleaning methods in the removal of remaining filling material during endodontic retreatment of curved canals. As well as other studies of endodontic retreatment have shown, no cleaning method was effective in completely removing the residual filling material (Cavenago *et al.* 2014, Rosa *et al.* 2015, Rodrigues *et al.* 2016, Silveira *et al*. 2018, Borges *et al.* 2019, Kaloustian *et al.* 2019b, Machado *et al.* 2019). The use of curved canals occurred because it is a more complex anatomy and presents a challenge for the clinician (Rosa *et al.* 2015, Rodrigues *et al.* 2017). Although this type of anatomy made it difficult to perform complementary cleaning methods, it was noted in Table 1 that all groups significantly reduced the amount of residual filling material, regardless of the region analyzed ($P<0.05$). Thus, the first null hypothesis was rejected. These results corroborate several studies in which curved canals were used and it was observed that different methods of agitation of the irrigation solution contributed to the reduction in the amount of filling material after retreatment (Cavenago *et al.* 2014, Rodrigues *et al.* 2018, Kaloustian *et al.* 2019b, Machado *et al.* 2019). Thus, even if the results of the present study demonstrated that residual filling material still remained in the root canals, it is important to emphasize the need to use a complementary cleaning method after retreatment.

The results of the present study also showed that there was no significant difference among cleaning methods in the removal capacity of residual filling material ($P>0.05$). Thus, the second null hypothesis was confirmed. Ultrasound activated irrigation (UAI) has been one of the most widely used and researched irrigation methods, so it was one of the methods chosen for this study. This type of irrigation can be performed in a passive way (passive ultrasonic irrigation - PUI), in which the instrument is inserted into the canal with irrigation solution and then activated by an ultrasound, being necessary the renewal of the irrigant every cycle; and can be performed continuously (continuous ultrasonic irrigation - CUI), in which the irrigating solution is delivered at the same time as the instrument is activated within the root canal (Bueno *et al.* 2019, Chan *et al.* 2019). The PUI results obtained in the present study corroborate with the majority of the studies in which they observe an improvement in the removal of material remaining probably by the formation of cavitation in the irrigation solution and acoustic microstreaming (Jiang *et al.* 2016, Rodrigues *et al.* 2017, De-Deus *et al.* 2019). However, there is no standard as to the amount of remaining filling material removed and this should occur due to the variations that occur in the methodologies of the studies such as canal anatomy, type of endodontic cement used, obturation technique employed and time/number of activation cycles.

Although the CUI seems to be related to a greater efficiency because of the activation and irrigation concomitantly, there is a shortage of studies in the literature that evaluate this method, and there are studies that show better results (Bueno *et al.* 2019) and worse than PUI (Chan *et al.* 2019). In the present study, CUI significantly reduced the amount of material remaining, but although there were no significant differences with the other groups, the percentage of removal was lower than PUI and Eddy. Regarding the types of inserts used in the PUI and CUI, there was no difference between them, even though both were manufactured with different materials (NiTiSonic - NiTi, Irrisafe, stainless steel).

The Eddy instrument presented a significant reduction in the amount of remaining filling material, corroborating with the results found by Kaloustian *et al* (2019a). The effectiveness of this instrument is related, according to the manufacturers, to the formation of cavitation and acoustic streaming within the irrigant produced by the high frequency (6000 Hz) to which the polymer tip (Eddy) is used (Kaloustian *et al.* 2019a). However, this effect is still not well defined since Macedo *et al* (2014) demonstrated that sonic devices do not produce cavitation due to low frequency. However, new studies need to be conducted because the Eddy instrument (6000 Hz) is used at a frequency significantly higher than that tested in the previous study (190 Hz) (Macedo *et al.* 2014).

As with the other groups, the XPendo Finisher R was related to a reduction in the volume of filling material, both in the apical region and in the whole canal. These results corroborate with other studies that observed great efficiency of this instrument that was specially fabricated for this stage (Silva *et al.* 2018, Campello *et al.* 2019, De-Deus *et al.* 2019, Machado *et al.* 2019). However, the reduction percentage in this study was lower than those obtained in these previous studies, regardless of the region analyzed. These results can be related to the type of anatomy, technique of obturation, time of storage of the tooth after the obturation and time of activation. Regarding the effectiveness of XPendo Finisher R, the results should be related to the type of alloy that the instrument is manufactured (MaxWire; FKG) that has the ability to increase its contact area when it is in body temperature leading to a greater mechanical action of the instrument on the walls of the root canal (De-Deus *et al.* 2019).

Other studies should be conducted in order to find ways to further optimize the removal of this remaining filling material as a way to obtain an increase in success rates in endodontic retreatment. Maybe, instruments that touch more effectively against canal walls or the combination of methods may result in a more effective removal, as demonstrated by Rivera-Pena *et al* 2018 where a specific ultrasonic insert was developed to mechanically remove the remaining filling material.

CONCLUSIONS

None of the additional cleaning methods were able to completely remove the remaining filling material. All methods were effective in reducing the amount of filling material, with no difference among them.

Conflict of interest The authors declare that they have no conflicts of interest.

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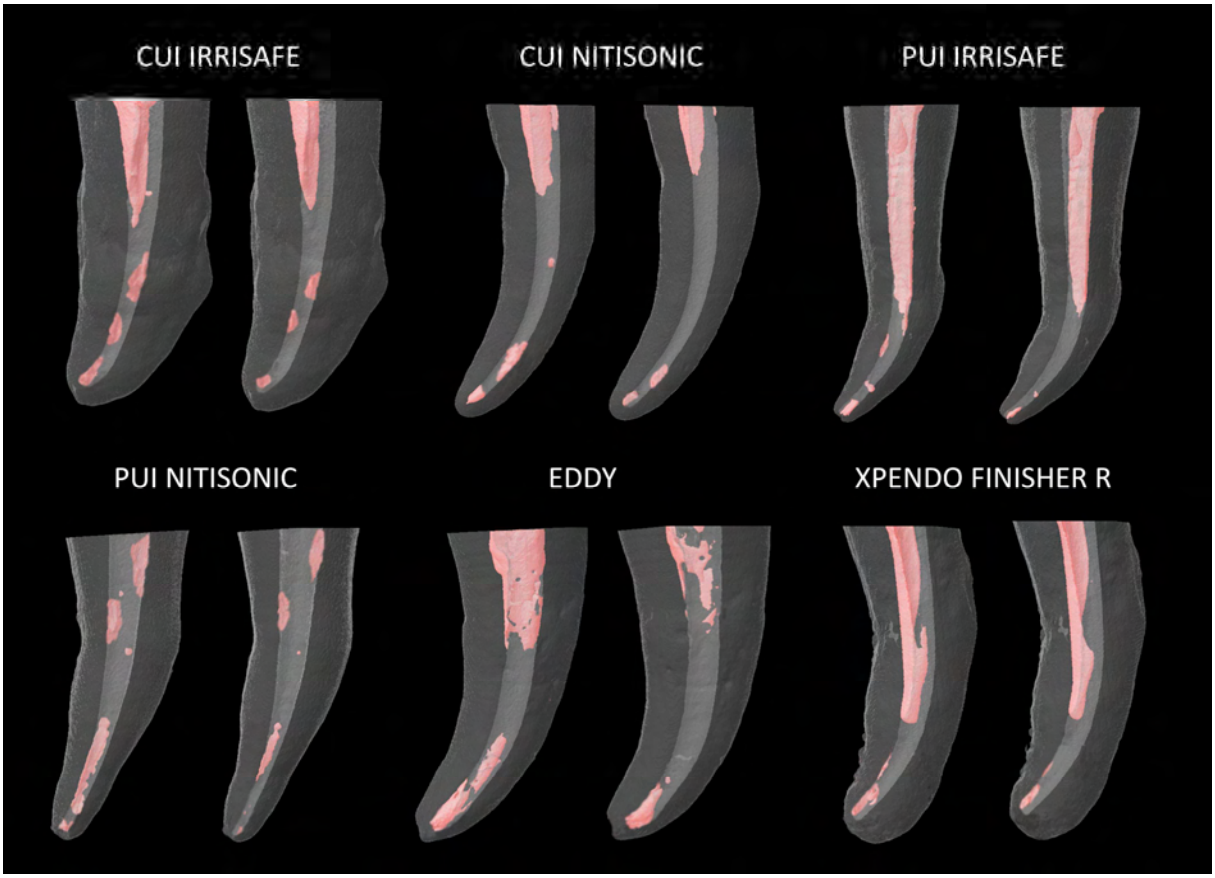
CUI IRRISAFE
CUI NITISONIC
PUI IRRISAFE
PUI NITISONIC
EDDY
XPENDO FINISHER R

Table 1. Median, minimum and maximum values of the volume in mm3 and the percentage of remaining filling material removed after the use of the different complementary cleaning methods.

Complementary methods	Regions	Remaining filling material before complementary methods (mm3)	Remaining filling material after complementary methods (mm3)	% of removal filling material with complementary methods
CUI IRRISAFE	TOTAL	0.93 (0.1-4.5)^{aA}	0.80 (0.1-4.4)^{B}	6.17 (2.2-77.5)^{a}
CUI NITISONIC		1.83 (0.1-7.6)^{aA}	1.62 (0.1-6.9)^{B}	8.18 (1.1-47.1)^{a}
PUI IRRISAFE		1.38 (0.3-4.4)^{aA}	1.26 (0.2-4.1)^{B}	10.82 (3.9-52.7)^{a}
PUI NITISONIC		1.61 (0.1-4.3)^{aA}	1.41 (0-3.9)^{B}	13.39 (1.4-79.1)^{a}
EDDY		0.96 (0.1-2.2)^{aA}	0.75 (0.1-1.9)^{B}	19.18 (9.1-48.9)^{a}
XP ENDO FINISHER R		1.25 (0.1-4.1)^{aA}	1.19 (0.1-4.1)^{B}	4.80 (1.3-63.3)^{a}
CUI IRRISAFE	APICAL	0.08 (0-0.2)^{aA}	0.05 (0-0.1)^{B}	17.38 (1.1-58.3)^{a}
CUI NITISONIC		0.14 (0.01-2.1)^{aA}	0.11 (0-2.1)^{B}	18.98 (1.2-99.1)^{a}
PUI IRRISAFE		0.19 (0.02-0.7)^{aA}	0.14 (0.01-0.7)^{B}	28.46 (8.1-85.3)^{a}
PUI NITISONIC		0.12 (0.01-0.8)^{aA}	0.07 (0-0.8)^{B}	50.76 (2.2-99.5)^{a}
EDDY		0.09 (0.01-0.2)^{aA}	0.05 (0.01-0.1)^{B}	45.22 (1.1-97.5)^{a}
XP ENDO FINISHER R		0.10 (0.01-0.2)^{aA}	0.09 (0-0.2)^{B}	15.64 (1.4-33.3)^{a}

Different lowercase letters in the same column indicate significant difference among groups, according to the region analyzed ($P<0.05$).
Different capital letters on the same line indicate significant difference within the same group ($P<0.05$).

3 Discussion

3 DISCUSSION

The aim of the articles I and II were to evaluate the preparation of curved canals and the cyclic fatigue resistance of new and used reciprocating instruments with differents types of heat treatment (Reciproc Blue - RB, WaveOne Gold - WOG, and ProDesign R - PDR).

The presence of curved canals can be challenging during root canal preparation and could not be clearly detected by periapical radiographs, which can cause undesirable shaping errors (YAMMINE et al., 2017; VALLABHANENI et al., 2017). During all the studies, single-rooted tooth with oval shaped canal with root curvatures ranging from 15° to 35° were used. The specimens were paired according to the degree of curvature using the method proposed by SCHNEIDER (1971). In this study I, the apical and total root canal volumes were measured and statistically analyzed, showing no significant difference among the groups ($P>0.05$) (Table 1 of the article 1).

After root canal preparation, the increase in root canal volume, percentage of untouched areas, and canal transportation were assessed by micro-CT using instruments with tip size 25 and complemented with large apical preparation size. The methodology used in this study has been extensively used in several previous studies because it is an accurate and non-destructible method (DE-DEUS et al., 2017; DUQUE et al., 2017; MARKS DUARTE et al., 2018).

There was no statistical difference in the percentage of volume increase (apical and total) among the three systems tested, except for the total volume after use of the larger instrument, where WOG 35.06 presented a higher volume ratio than PDR 35.05 ($P<0.05$). Untouched areas were evaluated on the apical portion because it is the most critical area for cleaning and shaping (RODRIGUES et al., 2017b; SIQUEIRA et al., 2018). There was no statistical difference among the groups ($P>0.05$). However, the WOG groups presented the lowest percentage of untouched areas for both sizes, followed by RB and PDR. The possible explanation for the results obtained for volume and untouched areas can be related to the different design features of the instruments. Previous studies have shown that the cross-sectional area and taper of WOG is larger than that of the PDR (ALCALDE et al., 2018a; SILVA et al., 2018a), which could lead to less metal mass volume. Therefore, we could speculate that the greater metal mass volume could favor a greater increase in root canal volume and reduce the percentage of untouched areas.

Despite the difference in the NiTi alloy among the instruments, there were no statistically significant differences in canal transportation (P>0.05). These findings are in line with those of other studies that showed that RB and WOG presented similar shaping ability (BURKLEIN et al., 2018; KESKIN et al., 2018). In addition, heat-treated instruments tend to present greater centering ability than the conventional NiTi alloy (BURKLEIN et al., 2018; DUQUE et al., 2017; OZYÜREK et al., 2017). There are no reports about the shaping ability of PDR instruments; however, FROTA et al. (2018) reported that PDR had a lower rate of foraminal deformation in comparison to Reciproc and WaveOne, which indicates suitable centering ability.

The within-group comparison showed a significant increase in root canal volume and a low percentage of untouched areas when the root canal was prepared with larger instruments (P<0.05). In addition, the root canal shape was maintained in comparison with size 25 instruments. These findings corroborate those of other studies, which reported that apical preparation size can be obtained using instruments larger than size 25, allowing greater microbial reduction, flowability of the irrigating solution, and reduction of debris at the apical portion (SIQUEIRA et al., 2018; RODRIGUES et al., 2017b; PÉREZ et al., 2018).

The instruments used for root canal preparation were also subjected to the cyclic fatigue test and compared with the new instruments. The cyclic fatigue test used was validated and published by MARKS DUARTE et al. (2018) and KLYMUS et al. (2018). Although previous studies suggested a dynamic cyclic fatigue model to test the cyclic fatigue resistance of NiTi instruments (KESKIN et al., 2017; KELES et al., 2019), as it models approximate a clinical use, this model has some limitations. First, the instruments being tested are not constrained in a precise trajectory. Moreover, the speed and amplitude of the axial movements could be standardized in a dynamic model, but these variables are completely subjective and it is doubtfull that they are constant and reproducible in a clinical situation (WAN et al., 2011). For this reason, aiming to minimize confounding causes by other mechanisms of instrument separation apart from cyclic fatigue, the static model was selected in the present study.

The new instruments from the PDR groups presented the highest time to fatigue and number of cycles than did RB and WOG (P<0.05) (Table 1 of the article 2). Our findings corroborate those of previous reports that showed that PDR is more resistant to fatigue than are RB and WOG (ALCALDE et al., 2018a; SILVA et al., 2018a). These findings are probably related to the different design of the instruments and to the type of heat treatment. PDR is manufactured with CM technology, which has greater flexibility and cyclic fatigue resistance as compared to Reciproc Blue and WaveOne Gold (SILVA et al., 2016; ALCALDE et al., 2017). In addition, PDR instruments have a smaller taper (0.06 and 0.05) than RB (0.08 and 0.06) and WOG (0.07 and 0.06), which could affect mechanical properties during the cyclic fatigue test (DE MENEZES et al., 2017; ALCALDE et al., 2018a). The RB 25.08 and 40.06 presented greater cyclic fatigue resistance than did WOG 25.07 and 35.06 ($P<0.05$). Although RB has a greater taper than WOG, the S-shaped cross-section of RB led to a smaller metal mass volume than did the parallelogram cross-section of WOG, which increases the flexibility of the instruments and explains our results (ALCALDE et al., 2018a; SILVA et al., 2018a).

The cyclic fatigue resistance of reciprocating instruments with tip size 25 was evaluated by several authors (SILVA et al., 2016; ALCALDE et al., 2017; KLYMUS et al., 2018). In addition, information on the mechanical properties of the instruments with larger tip size is lacking. Previous studies have reported that larger apical preparation brings some benefits to endodontic treatment (RODRIGUES et al., 2017b; PÉREZ et al., 2018; SIQUEIRA et al., 2018). Therefore, this study evaluated the cyclic fatigue resistance of reciprocating instruments with 40 and 35 tip sizes. ADIGUZEL et al. (2017) evaluated the cyclic fatigue resistance of WOG 45.05 and of WaveOne 40.08 (WO) reciprocating instruments. WOG 45.05 had a greater cyclic fatigue resistance than did WO 40.08. TOPÇUOGLU et al. (2017) showed that Reciproc Blue 40.06 had greater cyclic fatigue resistance than Reciproc. According to those authors, the results can be explained by the heat treatment of WOG and greater flexibility of Reciproc Blue (ADIGUZEL et al., 2017; TOPÇUOGLU et al., 2017).

Some studies have reported that reciprocating instruments can be safely used in three posterior teeth (BUENO et al., 2017). During root canal preparation, the instruments accumulate cyclic and torsional stress, which could lead to fatigue (WOLCOTT et al., 2006; MADARATTI et al., 2008; BUENO et al., 2017). This explains why this study used the instruments to prepare three mandibular premolars and evaluated their cyclic fatigue resistance.

Among the used instruments, PDR 25.06 showed no significant difference when compared with RB 25.08 ($P>0.05$). WOG 25.07 presented the lowest cyclic fatigue resistance among the groups ($P<0.05$). PDR 35.05 had more cyclic fatigue resistance than did RB 40.06 and WOG 35.06 ($P<0.05$). However, RB 40.06 was not significantly different from WOG 35.06 ($P>0.05$). This is probably related to the large tip size of RB 40.06 in comparison with WOG 35.06. There are no reports evaluating the cyclic fatigue resistance of these instruments after root canal preparation.

The within-group comparison revealed that cyclic fatigue resistance of the PDR 25.06, WOG 25.07 and 35.06 was significantly affected by simulated clinical use ($P<0.05$), while RB 25.08, 40.06 and PDR 35.05 were not affected ($P>0.05$).

In article III, the objective was to evaluate the quality of preparation of curved canals, torsional fatigue, and cyclic fatigue of new and used instruments of three rotary systems (BT-Race – BTR, Sequence Rotary File – SRF and ProDesign Logic – PDL) with different types of NiTi alloys. Several studies have demonstrated numerous benefits when this preparation is greater than a #25 instrument (RODRIGUES et al., 2017b; PÉREZ et al., 2018; SIQUEIRA et al., 2018). Therefore, in the present study, the three rotary systems had the finishing instrument size 35. Probably, because of the standardization of the final diameter and close taper (BTR 0.04, SRF 0.04, and PDL 0.05), there was no significant difference among the groups regarding the percent volume increase ($P>0.05$), even knowing that the final instruments present different types of cross sections and NiTi alloys (BTR - triangular section and conventional NiTi, SRF - triangular convex section and NiTi Blue, PDL – S-shaped section and NiTi CM).

An important factor during the biomechanical preparation of curved canals is the maintenance of their path (YAMMINE et al., 2017; PINHEIRO et al., 2018). Therefore, we analyzed canal transportation and centering ability of the systems in the apical region (last 4 mm), which corresponds to the region of the curvature (Table 1 of the article 3). There were no significant differences among the groups ($P>0.05$) for any of the analyses. Regarding canal transportation, the three groups presented values close to 0, i.e., lower than 0.3, which is a threshold value with no negative impact on the prognosis of endodontic treatment (PINHEIRO et al., 2018). Regarding centering ability, it is known that, according to the formula proposed by GAMBILL et al. (1996), the closer to 1, the better the centering ability. Although no significant differences were noted, PDL obtained values closer to 1, followed by

SRF and BTR, respectively. This can be mainly explained by the types of alloy used by the systems. PDL uses s CM alloy and SRF utilizes a Blue alloy. BTR has a conventional NiTi alloy, and several studies have demonstrated that heat-treated NiTi have greater flexibility and better maintenance of the canal path than do conventional alloys (DUQUE et al., 2017; FROTA et al., 2018; PINHEIRO et al., 2018).

Because these systems are relatively new in the market, few studies have analyzed quality of preparation. Most of these studies revealed similar results for the behavior of BTR to the ones found in the present study (BÜRKLEIN et al., 2015; BRASIL et al., 2017). PINHEIRO et al. (2018) observed that, although there was no statistical difference, PDL has better centering ability than that observed in different heat-treated rotary systems, in line with the results of this study.

Another important factor during biomechanical preparation of curved canals is the creation of the glide path, since it can improve the quality of preparation and reduce the risk of fracture of shaping instruments (DE-DEUS et al., 2016; ALCALDE et al., 2018b; HARTMANN et al., 2018; SANTOS et al., 2018). Therefore, most rotary systems have a specific instrument for this role. Generally, glide path instruments show high variability in tip diameter, taper, cross-section, and type of NiTi alloy among systems. These factors can contribute to different behaviors of the instruments (ALCALDE et al., 2018b). In the present study, glide path instruments were used in three teeth with curved canals and then subjected to torsional fatigue test, which analyzed maximum torque (N.cm) and maximum angular deflection (o). Concomitantly, the same instruments, although new, were also subjected to the same test using a previously validated methodology (table 2 of the article 3) (ALCALDE et al., 2018a; SANTOS et al., 2018).

The analysis of maximum torque of the new and used instruments showed that SRF 15.04 presented higher values than did PDL 25.01 and BTR 10.06 ($P<0.05$). These findings can be explained by the fact that SRF has a quadrangular cross section and a larger tip diameter than does BTR, which has a triangular cross section, with a smaller amount of metal mass in initial millimeters. Moreover, although PDL and SRF both have a quadrangular cross section, PDL has a lower taper (0.01) and CM NiTi alloy, with lower torsional resistance (ACOSTA et al., 2017; ALCALDE et al., 2018b). One factor that could influence torsional stress is the rotational speed per minute (RPM); however, HA et al. (2017) demonstrated that it does not alter torsional fatigue. It should be emphasized that both SRF and PDL maintained the same mean maximum torque (0.4 and 0.2, respectively) after simulated clinical use, while in BTR it decreased from 0.2 to 0.1. The fact that torsional fatigue did not change in SRF and PDL after clinical use may be related to the heat treatment they both had. As BTR does not have heat treatment for its alloy, torsional fatigue resistance decreased, corroborating the findings of a previous study that analyzed instruments with conventional NiTi alloys (VIEIRA et al., 2009).

Regarding angular deflection, both in the evaluation of new and used instruments, PDL 25.01 obtained significantly better results than did SRF 15.04 and BTR 10.06, respectively ($P<0.05$). This variable is directly related to the type of heat treatment of the instrument and to its taper, where the more flexible the instrument, the greater the angle of deflection (ALCALDE et al., 2018b; NISHIJO et al., 2018). There are no studies in the literature evaluating the torsional fatigue of BTR and SRF systems for comparison of the results obtained. Only one study evaluated PDL 25.01 and obtained results similar to those of the present study (ALCALDE et al., 2018b). In addition, it should be noted that the angular deflection of the three instruments was affected by clinical use. This may have occurred because, in addition to torsional fatigue, the instruments used in the preparation of the curved canals were also subjected to cyclic fatigue, leading to a reduction in angular deflection.

After creating the glide path, the root canal is shaped by the instruments. When these instruments work in a curved canal, they suffer cyclic fatigue because of tensile and compressive forces at the maximum point of curvature (MARKS DUARTE et al., 2018; SILVA et al., 2018a). In the study III, the new and used finishing instruments (size 35) were subjected to the cyclic fatigue test to verify their safety in canals with moderate curvature (table 3 of the article 3). In the analysis of the time necessary until fracture of the instruments, both new and used, PDL 35.05 demanded significantly longer time than did SRF 35.04 and BTR 35.04, respectively ($P<0.05$). The same results were also observed for the number of cycles, since this varies according to the speed used ($P<0.05$). The literature is very scarce when it comes to studies on the mechanical properties of the systems tested. DE MENEZES et al. (2017) also obtained better behavior for PDL even when compared to heat-treated Gold instruments. These results might have been obtained due to the design of the instrument (S-shaped cross-section), but mainly to the heat treatment CM of PDL, which provides greater flexibility and resistance to cyclic fatigue (ALCALDE et al., 2017; DE MENEZES et al., 2017; ALCALDE et al., 2018a). As to the intermediate results obtained for SRF, which has a Blue heat treatment, an analogy can be made with the findings of ALCALDE et al. (2018a) and SILVA et al. (2018a), where the instrument with Blue heat treatment obtained good results but worse ones than those of the instrument with CM heat treatment. In relation to BTR, made of conventional NiTi alloy, several studies have shown that this type of alloy has less resistance to cyclic fatigue than do NiTi instruments with some type of heat treatment (GAO et al., 2010; KAVAL et al., 2016; SILVA et al., 2016). Another factor that could influence cyclic fatigue strength is the speed used for each instrument. However, a study revealed no influence of speed, considering the design of the instrument and the type of alloy it is made of to be the most important factors (GAO et al., 2010). Note that none of the finishing instruments tested in the present study were significantly affected by clinical use. This may have occurred because the test was performed with the finishing instrument, which does not suffer as much stress as the first ones of the shaping.

The objective of the article IV was to evaluate the ability of different mechanized systems (Reciproc, Reciproc Blue, Pro-R and ProDesign Logic RT) in the ability to remove filling material in canals with moderate curvature, besides, to evaluate the resistance to cyclic fatigue of instruments size 25 and .08 taper and if simulated clinical use influences in the cyclic fatigue.

Several studies have been conducted to evaluate different removal procedure techniques of the root canal and all are unanimous that no method is able to completely filling material remove (CANALI et al., 2019; DE-DEUS et al., 2018; BORGES et al., 2019). These results corroborate with the data obtained in the study IV in which, regardless of the kinematics and characteristics of the instruments used, all presented residual filling material (Table 1 of the article IV).

For this study, single-rooted tooth with oval shaped canal with curvature were used, which were prepared and subsequently filled. The groups were divided according to the degree of curvature and the volume of total and apical filling material. The results shows that there were no significant differences among the systems regarding the volume of initial, total and apical filling material, indicating a correct sample pairing ($P>0.05$). In addition, in both evaluated regions, all the systems significantly decreased the volume of filling material after the retreatment procedures where instruments of size 25 were used and complemented with instruments of size 40 ($P<0.05$). These results corroborate with other studies that point out the need to use an additional large instrument to improve the removal of filling material in order to achieve a better cleaning of root canal systems (RODRIGUES et al., 2017a; SILVA et al. 2017; DE-DEUS et al., 2018).

Regarding the comparison among the groups regarding the volume of remaining filling material, it can be observed that, in the apical region, there were no significant differences among groups, however, in total, ProDesign Logic RT group remained significantly less material of Reciproc Blue and Pro-R ($P<0.05$) and with no difference for Reciproc ($P>0.05$). The literature is controversial when comparing the filling removal capacity using reciprocating and rotational kinematics. Studies have shown a better performance with reciprocating instruments (BERNARDES et al., 2016; BAGO et al., 2019), rotary (ALVES et al., 2016; JORGENSEN et al., 2017) and both presenting similar results (RODIG et al., 2014; DELAI et al., 2019). A possible explanation for the results found in the present study may be related to the design of the instruments. While Reciproc, Reciproc Blue and Pro-R reciprocating instruments have an S-shaped cross-section, ProDesign Logic RT 25.08 has a triple helix section. In addition, Reciproc and Reciproc Blue present variable taper, decreasing as it goes towards the cervical while the ProDesign Logic RT system has fixed taper. These characteristics make the ProDesign Logic RT instruments have a greater volume of metallic mass and consequently there may be a greater contact of the instruments in the walls of the root canal removing a larger volume of filling material. Another factor that may have influenced the results is the continuous rotation kinematics used in ProDesign Logic RT which has the tendency to displace debris in the coronal region, while the reciprocating kinematics there is a controversy of what actually occurs, and some studies state that there is a greater displacement apically (ALVES et al., 2016).

The ProDesign Logic RT instrument was significantly faster than Reciproc, Reciproc Blue and Pro-R ($P<0.05$), with respect to the working time by the size 25 instrument to reach working length (Table 2 of the article 4). This result seems to be directly related to the kinematic/velocity combination and the number of instruments used. The rotational kinematics have a screwing effect, which the reciprocating kinematics does not have, which favors the penetration of the instrument into the filling material (ALVES et al., 2016). Along with this, ProDesign Logic RT used 3x higher speed also contributed to this instrument penetrating more easily and achieving significantly faster working length. Studies in the literature comparing different kinematics uses rotational systems that present more than one instrument in the technique and are used at lower speeds while reciprocating systems are unique instruments (ALAKABANI et al., 2018; BAGO et al., 2019; DELAI et al., 2019).

These variations may lead to results different from those found in the present study where the rotational system used had only a single instrument and at a speed of 900 RPM.

For the analysis of resistance to cyclic fatigue of the instruments, a methodology already widely used by several authors was used (KLYMUS et al., 2008; MARKS DUARTE et al., 2018). One of the objectives of this study was to verify the resistance to cyclic fatigue of 4 instruments of size 25 and .08 taper presenting different types of thermal treatment and design in two different situations: new instruments, without any use, and after the use in the endodontic retreatment of a single-rooted tooth with oval shaped canal with curvature. The results showed that there were significant differences among the instruments in both situations. The results showed a better performance of the heat-treated instruments with controly memory (CM) technology (Reciproc Blue and ProDesign Logic RT), corroborating with several other studies (SILVA et al., 2016; DE-DEUS et al., 2017). Initially, the time required until the instrument fracture showed Reciproc Blue with more resistance than Reciproc, Pro-R and ProDesign Logic RT ($P<0.05$), however, when the number of cycles was analyzed, which takes into account the speed used for each system, ProDesign Logic RT also showed significantly higher cyclic fatigue resistance than Reciproc and Pro-R ($P<0.05$), with no difference for Reciproc Blue ($P>0.05$). The results were similar for both new instruments and after simulated clinical use. Although ProDesign Logic RT exhibits the same type of heat treatment as the ProDesign R instrument (Easy Dental Equipment, Belo Horizonte, Brazil), a reciprocating instrument for canal preparation in which some studies showed greater resistance to cyclic fatigue than the Reciproc Blue (ALCALDE et al., 2018a; SILVA et al., 2018a), other factors interfered so that the results found were not similar. ProDesign Logic RT is a rotating instrument where the literature has shown to have lower resistance to cyclic fatigue than reciprocating instruments (LOPES et al., 2013; FERREIRA et al., 2017) and also have a triple-helix cross-section while ProDesign R presents a cross-section in S. This shows that the type of heat treatment is not the only one that influences the mechanical properties of the instrument, but other factors such as kinematics and design affect directly.

Regarding the Reciproc and Pro-R instruments, both have M-Wire thermal treatment NiTi alloy and similar design, where the difference between them is basically the reciproc variable taper while the Pro-R presents fixed taper. Because this variation was almost imperceptible, the results of the cyclic fatigue resistance of both were very close and without significant difference ($P>0.05$). However, both showed less cyclical fatigue resistance than Reciproc Blue and ProDesgin Logic RT ($P<0.05$). There are no papers in the literature evaluating Pro-R and ProDesign Logic RT for results to be confronted. The best performance of Reciproc Blue on Reciproc corroborates with other studies which point out that it is directly related to the heat treatment with Blue technology of Reciproc Blue since both instruments have identical design (DE-DEUS et al., 2017; PLOTINO et al., 2018). Although ProDesign Logic RT has a fixed taper and a triple helix cross section, thus presenting a greater volume of metal mass than the other instruments (Reciproc and Reciproc Blue - S-section and variable taper, Pro-R - section in S and fixed taper), it presented a significantly higher number of cycles than the M-Wire heat treatment instruments (Reciproc and Pro-R) for both new instruments and after clinical use. Thus, the thermal treatment with CM technology of ProDesign Logic RT must have been the great differential for the results found, since this technology is known for its great flexibility and resistance to cyclic fatigue (DE MENEZES et al., 2017; ALCALDE et al., 2018a; SILVA et al., 2018a).

The influence of simulated clinical use was also an objective of the study IV. However, the results pointed out that none of the systems tested were affected by the use in endodontic retreatment of a single-rooted tooth with oval canal with the curvature. There are no studies in the literature evaluating the effect of the simulated clinical use on the mechanical properties of the instruments. Although moderate curvature canals were used in the present study, the fact that clinical use did not influence cyclic fatigue may be related to the fact that single canal teeth were used. Therefore, other studies should be conducted using teeth with more than one canal to observe whether simulated clinical use affects the resistance to cyclic fatigue of instruments in situations of greater complexity.

Lastly, the objective of the article V was to evaluate and compare the efficacy of six different complementary cleaning methods in the removal of remaining filling material during endodontic retreatment of curved canals. As well as other studies of endodontic retreatment have shown, no cleaning method was effective in completely removing the residual filling material (CAVENAGO et al., 2014; DA ROSA et al., 2015; RODRIGUES et al., 2016; SILVEIRA et al., 2018; BORGES et al., 2019; KALOUSTIAN et al., 2019; MACHADO et al., 2019). Table 1 of the article V shows that all groups significantly reduced the volume of residual filling material, regardless of the region analyzed ($P<0.05$). These results corroborate several studies in which curved canals were used and it was observed that different methods of agitation of the irrigation solution contributed to the reduction in the volume of filling material after retreatment (CAVENAGO et al., 2014; KALOUSTIAN et al., 2019; MACHADO et al., 2019). Thus, even if the results of the present study demonstrated that residual filling material still remained in the root canals, it is important to emphasize the need to use a complementary cleaning method after retreatment.

The results of the present study also showed that there was no significant difference among cleaning methods in the removal capacity of residual filling material (P>0.05). Ultrasound activated irrigation (UAI) has been one of the most widely used and researched irrigation methods, so it was one of the methods chosen for this study. This type of irrigation can be performed in a passive way (passive ultrasonic irrigation - PUI), in which the instrument is inserted into the canal with irrigation solution and then activated by an ultrasound, being necessary the renewal of the irrigant every cycle; and can be performed continuously (continuous ultrasonic irrigation - CUI), in which the irrigating solution is delivered at the same time as the instrument is activated within the root canal (BUENO et al., 2019; CHAN et al., 2019). The PUI results obtained in the present study corroborate with the majority of the studies in which they observe an improvement in the removal of material remaining probably by the formation of cavitation in the irrigation solution and acoustic microstreaming (JIANG et al., 2016; RODRIGUES et al., 2017a; DE-DEUS et al., 2019b). However, there is no standard as to the amount of remaining filling material removed and this should occur due to the variations that occur in the methodologies of the studies such as canal anatomy, type of endodontic cement used, obturation technique employed and time/number of activation cycles.

Although the CUI seems to be related to a greater efficiency because of the activation and irrigation concomitantly, there is a shortage of studies in the literature that evaluate this method, and there are studies that show better results (BUENO et al., 2019) and worse than PUI (CHAN et al., 2019). In the present study, CUI significantly reduced the volume of material remaining, but although there were no significant differences with the other groups, the percentage of removal was lower than PUI and Eddy. Regarding the types of inserts used, there was no difference between them, even though both were manufactured with different materials (NiTiSonic - NiTi, Irrisafe, stainless steel).

As with the other groups, the XP-endo Finisher R was related to a reduction in the volume of filling material, both in the apical region and in the whole canal. These results corroborate with other studies that observed great efficiency of this instrument that was specially fabricated for this stage (SILVA et al., 2018b; CAMPELLO et al., 2019; DE-DEUS et al., 2019b; MACHADO et al., 2019). However, the reduction percentage in this study was lower than those obtained in these previous studies, regardless of the region analyzed. These results can be related to the type of anatomy, technique of obturation, time of storage of the tooth after the obturation and time of activation. Regarding the effectiveness of XP-endo Finisher R, the results should be related to the type of alloy that the instrument is manufactured (MaxWire; FKG) that has the ability to increase its contact area when it is in body temperature leading to a greater mechanical action of the instrument on the walls of the root canal (DE-DEUS et al., 2019b).

Other studies should be conducted in order to find ways to further optimize the removal of this remaining filling material as a way to obtain an increase in success rates in endodontic retreatment. Maybe, instruments that touch more effectively against canal walls or the combination of methods may result in a more effective removal, as demonstrated by RIVERA-PENA et al. (2018) where a specific ultrasonic insert was developed to mechanically remove the remaining filling material.

4 Conclusion

4 CONCLUSION

Based on the articles that make up this thesis, it can be concluded that:

Articles I and II - Reciproc Blue, WaveOne Gold, and ProDesign R reciprocating systems presented similar root canal shaping abilities even in larger apical preparation size. Additionally, larger apical preparation size significantly reduced the percentage of untouched areas of the canal. ProDesign R showed the highest resistance to cyclic fatigue and all systems could be safely used in three moderately curved single-rooted teeth. Besides, Reciproc Blue was not affected by simulated clinical use.

Article III – BT-Race, Sequence Rotary File, and ProDesign Logic rotary instruments were safe and presented similar quality in the shaping of canals with moderate curvature. However, different behaviors were observed in the mechanical properties of the instruments. In torsional fatigue, Sequence Rotary File 15.04 presented the highest torque values, ProDesign Logic 25.01 presented the highest values of angular deflection, and BT-Race 10.06 was the most frequently affected by simulated clinical use. ProDesign Logic 35.05 presented higher resistance to cyclic fatigue, followed by Sequence Rotary File 35.04, and the finishing instruments were not affected by simulated clinical use.

Article IV - ProDesign Logic RT had the least volume of remaining filling material and required a shorter working time to reach working length. Reciproc Blue and ProDesign Logic RT showed greater resistance to cyclic fatigue. Simulated clinical use did not affect any of the instruments.

Article V - None of the additional cleaning methods were able to completely remove the remaining filling material. All methods were effective in reducing the volume of filling material, with no difference among them.

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Appendix

APPENDIX A - DECLARATION OF EXCLUSIVE USE OF THE ARTICLE IN THESIS

We hereby declare that we are aware that the article **Effect of larger apical size on the quality of preparation in curved canals using reciprocating instruments with different heat thermal treatment** will be included in the Thesis of the student (Jussaro Alves Duque) and may not be used in other works of Graduate Programs at the Bauru School of Dentistry, University of São Paulo.

Bauru, June 04th 2019.

Print name: Jussaro Alves Duque

Signature Jussaro Alves Duque

Print name: Murilo Priori Alcalde

Signature

Print name: Victor de Moraes Cruz

Signature Victor Cruz

Print name: Mariana Maciel Batista Borges

Signature Mariana M. B Borges

Print name: Rodrigo Ricci Vivan

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Print name: Marco Antonio Hungaro Duarte

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Print name: Clovis Monteiro Bramante

Signature

APPENDIX B - DECLARATION OF EXCLUSIVE USE OF THE ARTICLE IN THESIS

We hereby declare that we are aware that the article **Cyclic fatigue resistance of NiTi reciprocating instruments after simulated clinical use** will be included in the Thesis of the student (Jussaro Alves Duque) and may not be used in other works of Graduate Programs at the Bauru School of Dentistry, University of São Paulo.

Bauru, June 04th 2019.

Print name: Jussaro Alves Duque

Signature JUSSARO Alves Duque

Print name: Murilo Priori Alcalde

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Print name: Emmanuel João Nogueira Leal Silva

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Print name: Rodrigo Ricci Vivan

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Print name: Marco Antonio Hungaro Duarte

Signature Marco A H Duarte

Print name: Clovis Monteiro Bramante

Signature

APPENDIX C - DECLARATION OF EXCLUSIVE USE OF THE ARTICLE IN THESIS

We hereby declare that we are aware that the article **EVALUATION OF ROOT CANAL PREPARATION AND MECHANICAL PROPERTIES OF NITI ROTARY INSTRUMENTS MANUFACTURED WITH DIFFERENT TYPES OF NITI ALLOYS** will be included in the Thesis of the student (Jussaro Alves Duque) and may not be used in other works of Graduate Programs at the Bauru School of Dentistry, University of São Paulo.

Bauru, June 04th 2019.

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Print name: Leticia Citelli Conti

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Print name: Rodrigo Ricci Vivan

Signature

Print name: Marco Antonio Hungaro Duarte

Signature Marco A H Duarte

Print name: Clovis Monteiro Bramante

Signature

APPENDIX D - DECLARATION OF EXCLUSIVE USE OF THE ARTICLE IN THESIS

We hereby declare that we are aware that the article **Evaluation of the quality in the retreatment and resistance to cyclic fatigue of mechanized systems with different thermal treatments** will be included in the Thesis of the student (Jussaro Alves Duque) and may not be used in other works of Graduate Programs at the Bauru School of Dentistry, University of São Paulo.

Bauru, June 04th 2019.

Print name: Jussaro Alves Duque

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Print name: Murilo Priori Alcalde

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Print name: Gabriela Gonçalez Piai

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Print name: Pedro Henrique Souza Calefi

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Print name: Rodrigo Ricci Vivan

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Print name: Marco Antonio Hungaro Duarte

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Print name: Clovis Monteiro Bramante

Signature

APPENDIX E - DECLARATION OF EXCLUSIVE USE OF THE ARTICLE IN THESIS

We hereby declare that we are aware that the article **Efficiency of ultrasonic, sonic and mechanical complementary cleaning methods in the removal of filling material remaining in curved canals** will be included in the Thesis of the student (Jussaro Alves Duque) and may not be used in other works of Graduate Programs at the Bauru School of Dentistry, University of São Paulo.

Bauru, June 04th 2019.

Print name: Jussaro Alves Duque

Signature JUSSARO Alves Duque

Print name: Murilo Priori Alcalde

Signature

Print name: Arthur Costa Lemos

Signature

Print name: Rodrigo Ricci Vivan

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Print name: Marco Antonio Hungaro Duarte

Signature Marco A H Duarte

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Annex

Annex A - Permission letter to include a published article from the International Endodontic Journal in this thesis.

03/06/2019 E-mail de Universidade de São Paulo - permission to reproduce article on Doctoral thesis

Jussaro Alves Duque <jussaroduque@usp.br>

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3 mensagens

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Hi, my name is Jussaro Alves Duque. I am an author of the article "

Effect of larger apical size on the quality of preparation in curved canals using reciprocating instruments with different heat thermal treatments" which was accepted in International Endodontic Journal.

this article is part of the Doctoral thesis and I would like to get permission to attach the article in the thesis. I tried to get permission on line. However, no success.

What I need to do?

Best Regards

--
Jussaro Alves Duque

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Annex B - Registration and approval of research on ethics committee

USP - FACULDADE DE ODONTOLOGIA DE BAURU DA USP

Plataforma Brasil

PARECER CONSUBSTANCIADO DO CEP

DADOS DA EMENDA

Título da Pesquisa: Análise da qualidade do preparo e do retratamento de diferentes instrumentos associados ou não a diferentes protocolos de agitação do irrigante

Pesquisador: Jussaro Alves Duque

Área Temática:

Versão: 2

CAAE: 88418518.4.0000.5417

Instituição Proponente: Universidade de São Paulo - Faculdade de Odontologia de Bauru

Patrocinador Principal: Financiamento Próprio

DADOS DO PARECER

Número do Parecer: 3.284.721

Apresentação do Projeto:

Emenda inserindo mais 42 participantes (dentes) e dois novos grupos com novas técnicas de instrumentação endodôntica com aumento de limas utilizadas.

Objetivo da Pesquisa:

Emenda alterando a proposta de análise inicial para expansão das análises.

Avaliação dos Riscos e Benefícios:

Não se alteraram do projeto original aprovado.

Comentários e Considerações sobre a Pesquisa:

Inseridos mais 42 participantes (dentes) e dois novos grupos com novas técnicas de instrumentação endodôntica com aumento de limas utilizadas.Justificado no projeto de pesquisa.

Considerações sobre os Termos de apresentação obrigatória:

A folha de rosto, projeto original e na plataforma brasil foram ajustados de acordo com a solicitação da emenda e há um novo termo de cessão de dentes anexado.

Conclusões ou Pendências e Lista de Inadequações:

Aprovado

Considerações Finais a critério do CEP:

A emenda apresentada pelo(a) pesquisador(a) foi considerada APROVADA na reunião ordinária do CEP de 17/04/2019, com base nas normas éticas da Resolução CNS 466/12. Ao término da

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pesquisa o CEP-FOB/USP exige a apresentação de relatório final. Os relatórios parciais deverão estar de acordo com o cronograma e/ou parecer emitido pelo CEP. Alterações na metodologia, título, inclusão ou exclusão de autores, cronograma e quaisquer outras mudanças que sejam significativas deverão ser previamente comunicadas a este CEP sob risco de não aprovação do relatório final. Quando da apresentação deste, deverão ser incluídos todos os TCLEs e/ou termos de doação assinados e rubricados, se pertinentes.

Este parecer foi elaborado baseado nos documentos abaixo relacionados:

Tipo Documento	Arquivo	Postagem	Autor	Situação
Informações Básicas do Projeto	PB_INFORMAÇÕES_BÁSICAS_1316898_E1.pdf	19/03/2019 18:57:28		Aceito
Folha de Rosto	Folha_rosto_emenda.pdf	19/03/2019 18:51:37	Jussaro Alves Duque	Aceito
Outros	Oficio_emenda.pdf	18/03/2019 15:40:24	Jussaro Alves Duque	Aceito
Outros	intencao_cessao_dentes.pdf	18/03/2019 14:53:43	Jussaro Alves Duque	Aceito
Projeto Detalhado / Brochura Investigador	Projeto_detalhado.docx	18/03/2019 14:39:55	Jussaro Alves Duque	Aceito
Orçamento	Orcamento.docx	19/04/2018 08:49:00	Jussaro Alves Duque	Aceito
Outros	Questionario_tecnico.pdf	18/04/2018 17:22:38	Jussaro Alves Duque	Aceito
Outros	cessao_de_dentes.doc	18/04/2018 17:19:48	Jussaro Alves Duque	Aceito
Declaração de Instituição e Infraestrutura	cep_docs_proj_pesquisa_carta_de_encaminhamento_termo_de_aquiescencia.pdf	18/04/2018 17:19:05	Jussaro Alves Duque	Aceito
TCLE / Termos de Assentimento / Justificativa de Ausência	Justificativa_TCLE.pdf	18/04/2018 17:03:29	Jussaro Alves Duque	Aceito
Declaração de Pesquisadores	Declaracao_de_compromisso_do_pesquisador.pdf	18/04/2018 17:02:15	Jussaro Alves Duque	Aceito
Cronograma	Cronograma.docx	18/04/2018 16:59:24	Jussaro Alves Duque	Aceito

Situação do Parecer:

Aprovado

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Continuação do Parecer: 3.284.721

Necessita Apreciação da CONEP:
Não

BAURU, 25 de Abril de 2019

Assinado por:
Ana Lúcia Pompéia Fraga de Almeida
(Coordenador(a))

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