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ORIGINAL ARTICLE

Apical transportation and surface characteristics of thermally-treated reciprocating instruments after endodontic reintervention

ABSTRACT

Aim: *To evaluate the apical transportation and surface characteristics of two thermally-treated reciprocating instruments after endodontic reintervention.*
Methodology: *Images of 42 resin blocks containing simulated canals were obtained. After instrumentation (WaveOne Gold Primary - 25.07), the simulated canals were obturated and new images were obtained. The blocks were distributed into two groups (n=21), WaveOne Gold (Medium - 35.06) and Reciproc Blue (R40 - 40.06). Each instrument was used for filling material removal and re-instrumentation of three simulated canals. After reintervention, new images of the blocks were obtained and superimposed on the initial ones to calculate the apical transportation. The surface characteristics of the instruments before and after continuous use were performed under [Scanning Electron Microscope (SEM)]. The Kruskal-Wallis test was applied to the data and complemented by Dunn's multiple comparison test (p<0.05).*
Results: *Both systems had similar apical transportation values, with no significant difference (p>0.05). WaveOne Gold with no use and after the first use showed a greater number of defects than Reciproc Blue with no use and after two uses (p<0.001). Reciproc Blue had a significant increase in the number of defects after the third use (p<0.001).*
Conclusions: *WaveOne Gold and Reciproc Blue systems provided minimal and similar apical transportation. The number of defects was greater for the WaveOne Gold system, which increased after endodontic reintervention.*

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Introduction

The main cause of endodontic treatment failure is persistent infection after chemical-mechanical preparation (1). As an alternative treatment for these cases, non-surgical endodontic reintervention should be considered the first choice (2). Therefore, the filling material must be removed, and new instrumentation and obturation of the root canal system performed (3).
Several techniques have been proposed for the filling material removal during endodontic reintervention (4, 5). Rotary and reciprocating instruments made from thermally-treated Ni-Ti alloy have shown great effectiveness (6, 7). Nevertheless, no technique or instrumentation system is capable of completely removing the obturation, leaving remnants of filling material attached to the root canal walls (4, 5). Furthermore, these instruments promote changes in the original root canal trajectory during filling material removal and re-instrumentation, especially in curved canals (8). For this reason, new instruments with modified cross-sections, asymmetrical motion, and advances in the thermomechanical treatment of Ni-Ti alloys have been proposed to maintain the original root canal shape (9, 10).
The instruments of the WaveOne Gold (Dentsply Maillefer, Ballaigues, Switzerland) and Reciproc Blue systems (VDW, Munich, Germany) are manufactured from specific thermally-treated Ni-Ti alloys (11). WaveOne Gold instruments have a two-dimensional parallelogram cross-section and variable taper (12), while Reciproc Blue instruments have an S-shaped cross-section with a regressive taper in the first three apical millimetres (13). Both are single-file systems, and according to their respective manufacturers, they must be used to prepare a maximum of three to four canals in the same patient. The continuous use of these instruments leads to their wear and deformation, increasing the risk of fracture (14, 15).
These instruments are submitted to a high level of stress during filling material removal and re-preparation, especially in multi-rooted teeth with curved canals (3, 4). Few studies have evaluated the changes in root canal morphology, such as apical transportation, after endodontic reintervention (16). Moreover, no study so far has assessed the topographic changes that may occur on the surface of these instruments after their continuous use.
The purpose of this *in vitro* study was to evaluate the apical transportation promoted by these two thermally-treated reciprocating instruments (WaveOne Gold and Reciproc Blue) during endodontic reintervention in simulated curved canals. The analysis of the surface characteristics of these instruments was also performed after their continuous use (filling material removal and re-preparation of the simulated canal). The null hypotheses tested were that there would be no difference between the different instrumentation systems regarding I) the apical transportation and II) the surface characteristics of the instruments after endodontic reintervention.

Materials and Methods

Simulated Root Canal Preparation and Obturation

The manuscript of this laboratory study has been written following the Preferred Reporting Items for Laboratory studies in Endodontology (PRILE) 2021 Guidelines (17) (Figure 1). In the present study, we used forty-two transparent blocks of polyester resin (IM do Brasil Ltda. São Paulo, Brazil) containing simulated canals with an angle of 40°, a radius of curvature of 3 mm, and 17 mm in length. The sample size was determined based on data from a pilot study. A bilateral test for associated samples (level of significance=0.05% and test power=0.85), recommended 42 samples.
Initially, the simulated root canals were prepared with the Primary instrument (25.07) of the WaveOne Gold system (Dentsply-Maillefer). The instrument was coupled to a 6:1 contra-angle device powered by an electric motor (X-Smart Plus, Dentsply-Maillefer), driven in a reciprocating motion, and introduced into the canal with light pressure in the apical direction, in back-and-forth movements, and maximum

amplitude of 3 mm. During the preparation of the cervical and middle thirds, the canal was irrigated with 1 mL of 2.5% NaOCl solution (Rio Química, São José do Rio Preto, Brazil), at each advancement and removal of the instrument for cleaning in sterile gauze. The irrigating solution was placed into the simulated canal with a 5-mL syringe (Ultradent, Salt Lake City, USA) and a 27-g needle (Endo-Eze; Ultradent) using back-and-forth movements. After, the working length was determined with a size 10 K-type instrument (Dentsply-Maillefer), inserted into the simulated canal in the apical direction until the tip was visualized at the apical foramen. The working length was set at 1 mm short of the apical foramen (16 mm). The apical finishing was performed as for the other root canal thirds until reaching the working length. At every three simulated canals prepared, the instrument was replaced by a new one, as recommended by the manufacturer.

After completion of the chemical-mechanical preparation, the simulated canals were obturated with gutta-percha cones (WaveOne Gold Primary; Dentsply-Maillefer) and an epoxy resin-based root canal sealer (AH Plus; Dentsply, Petrópolis, Brazil) by the Tagger's hybrid technique. The integrity of the obturation was meticulously visually inspected with the aid of magnifying glasses (×2.5). In instances where the artificial canal obturation exhibited bubbles, voids, and failures in the compaction of the filling material (18), the specimen was discarded from the final sample and replaced with a new resin block. The resin blocks were stored for seven days until the final setting of the root canal sealer.

Collection of Instruments and Scanning Electron Microscopy (SEM)

Seven brand-new instruments from the WaveOne Gold (Medium - 35.06) (Dentsply-Maillefer) and Reciproc Blue systems (R40 - 40.06) (VDW) were removed from their packaging materials and meticulously inspected under magnification (×4). Only instruments free of visible defects and irregularities were included in the study. The WaveOne Gold system instruments were numbered from 1 to 7, and the Reciproc Blue system instruments were numbered from 8 to 14. No previous cleaning treatment was performed on the instruments. The instruments were carefully handled with clinical forceps during all stages of this research, avoiding contamination by other materials that might compromise the analysis of their surface characteristics. The instruments were placed on metal stubs for initial assessment of their topography and surface characteristics under [Scanning Electron Microscopy (SEM)] (Jeol, JSM-IT500HR, Peabody, USA). Images from both sides of the active part of the instruments were obtained. The active part of each instrument was assessed at ×190 magnification, in three different portions: instrument tip, 2 mm, and 4 mm short of the instrument tip.

Endodontic Reintervention

After the initial SEM images acquisition, each one of the seven instruments of the tested systems was used for the filling material removal and re-instrumentation of three resin blocks containing the previously obturated simulated root canals. The resin blocks containing the simulated root canals were randomly distributed into 2 groups (n=21) (Random Sequence Generator; https://www.randomdraws.com/random-sequence-generator), according to the instrumentation system used for endodontic reintervention: WaveOne Gold (Medium - 35.06) and Reciproc Blue (R40 - 40.06). The same protocol for filling material removal and re-preparation was used for both systems.

Initially, each instrument was coupled to a 6:1 contra-angle device driven by an electric motor (X-Smart Plus, Dentsply-Maillefer), at 400 rpm, in a reciprocating motion. For the filling material removal and re-instrumentation of the simulated canal, each instrument was gradually inserted into the root canal three times, in the apical direction, with gentle pecking movements of a 3-mm amplitude limit. At each instrument removal for cleaning, 2 mL of 2.5% NaOCl solution (Rio Química) was used for root canal irrigation. The irrigating solution was placed into the simulated canal with a 5-mL syringe (Ultradent) and a 27-g needle (Endo-Eze; Ultradent) inserted to 2 mm short of working length using back-and-

During endodontic reintervention, instruments are subjected to a high level of stress. Few studies have assesseed the apical transportation after cyclic use of thermally-treated reciprocating instruments. Furthermore, no study so far has assessed the topographic changes that may occur on the surface of these instruments after their continuous use.

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After reintervention, new images were obtained supeimposed on the initial ones to calculate the apical transportation (ImageJ software; https://imagej.nih.gov/ij/download.html). The surface characteristics of the instruments before and after continuos use were assesse under Scanning Electron Microscope (SEM).The Kruskal-Wallis and Dunn's multiple comparision test were applied to the data ($p>0.05$).

Both systems had similar apical transportation ($p>0.05$). WaveOne Gold with no use and after the first use showed a greater number of defects than Rec1procB lue with no use and after two uses ($p<0.001$). Reciproc Blue had a significant crease in the number of defects after the third use ($p<0.001$).

WaveOne Gold and Reciproc Blue systems provided and similar apical transportation: the number of defects greater for the WaveOne Gold system, which increased after endodontic reintervention.

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

Figure 1 PRILE flowchart.

forth movements. These procedures were repeated until the instrument reached the working length (16 mm), and it was no longer possible to visualize filling material inside the simulated canal, in the active part of the instruments, and/or in suspension during the irrigating solution reflux. At the end of the simulated root canal re-instrumentation, a final irrigation protocol with 5 mL of 2.5% NaOCl solution (Rio Química) was performed. The simulated root canal preparation and re-preparation were performed by only one experienced Endodontics specialist to avoid any variables regarding the shaping ability of different operators.
At the end of each endodontic reintervention, the instrument was cleaned in an ultrasonic bowl (Cristófoli, Campo Mourão, Brazil) containing heated water and enzymatic detergent (Endozime; Medclean Comercial Ltda., Porto Alegre, Brazil) and submitted to a new SEM images acquisition, as previously described. After completion of the endodontic reintervention in the last block (third), the instrument was once again cleaned, and new SEM images were acquired.

SEM Analysis
To minimize the risk of bias, the analysis of the images obtained under SEM before and after endodontic reintervention was performed at different times, with an interval of 15 days between each one. The images were assessed by two previously calibrated and blinded examiners. The findings observed at different times were submitted to the Kappa test to assess intra- and inter-examiner agreement, until the establishment of rates greater than 0.7 for validation and reproducibility. The analysis of the surface characteristics of the instruments was performed at the same angle as the active part of the instruments, comparing the images obtained before and after their continuous use. The findings considered during the analysis were: active part of the instrument with irregular edges, grooves, microcavities, burrs, and/or debris attached to the instrument's surface (14, 15). A scoring system based on the number of defects present on the instrument's surface was used (14, 15) (Table 1).

Apical Transportation Analysis
For the apical transportation analysis, each resin block was photographed in a standardized manner, at two different times: after simulated root canal obturation and after endodontic reintervention. A digital camera (Canon EOS Rebel T5, Lake Success, USA), with a resolution of 18 megapixels, a macro lens of 100 mm, and a diaphragm opening of 4.5 was used for image acquisition. To standardize the distance between the camera lens and the resin block, the simulated root canals were positioned on a platform in the same position, at a focal distance of 32 cm. All pictures were taken under the same conditions, under ambient light.
With the aid of the ImageJ software (https://imagej.nih.gov/ij/download.html), the images of the simulated root

Table 1
Scoring system used to assess the presence of defects on the surface of instruments.

Score	Defects on the surface of instruments
1	Long axis of the instrument without any defect on its surface.
2	Long axis of the instrument with one to three areas of defects on its surface.
3	Long axis of the instrument with four to five areas of defects on its surface.
4	Long axis of the instrument with more than five areas of defects on its surface.

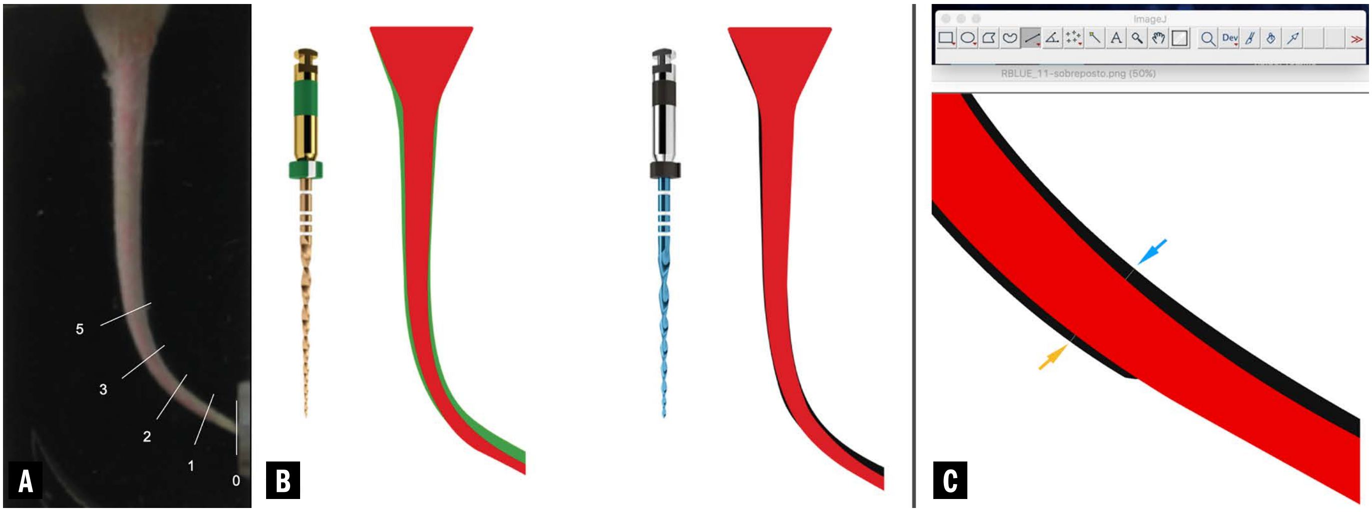

Figure 2
A) Resin block containing the simulated root canal. Measuring ruler for the four evaluated apical levels (mm).
B) Superimposed images of the simulated root canals before (red) and after endodontic reintervention (green - WaveOne Gold and black - Reciproc Blue).
C) Measurements on the outer surface (yellow arrow) of the root canal to the inner surface (blue arrow) (ImageJ software).

canals received different colours. Red for the obturated root canals (before endodontic reintervention), green for the root canals re-instrumented with the WaveOne Gold system, and black for the root canals re-instrumented with the Reciproc Blue system. The Adobe Photoshop CC (Adobe Systems Inc., San Jose, USA) software was used to superimpose the final images over the initial ones. The distance from the inner wall of the obturated root canal to the outer wall of the post-reintervention root canal was measured blindly by a single calibrated and trained examiner, with the ImageJ software. The equation AT=IS-OS was used to calculate the apical transportation of the simulated root canal, where IS represents the wear on the inner surface of the canal, and OS, the wear on the outer surface. The apical transportation was measured in four different reference points, corresponding to the 1st, 2nd, 3rd, and 5th millimetres below the root apex (Figure 2).

Statistical Analysis
The GraphPad InStat software (GraphPad Software, La Jolla, USA) was used to perform the statistical analysis. The dataset for apical transportation did not have a normal distribution (The Shapiro-Wilk

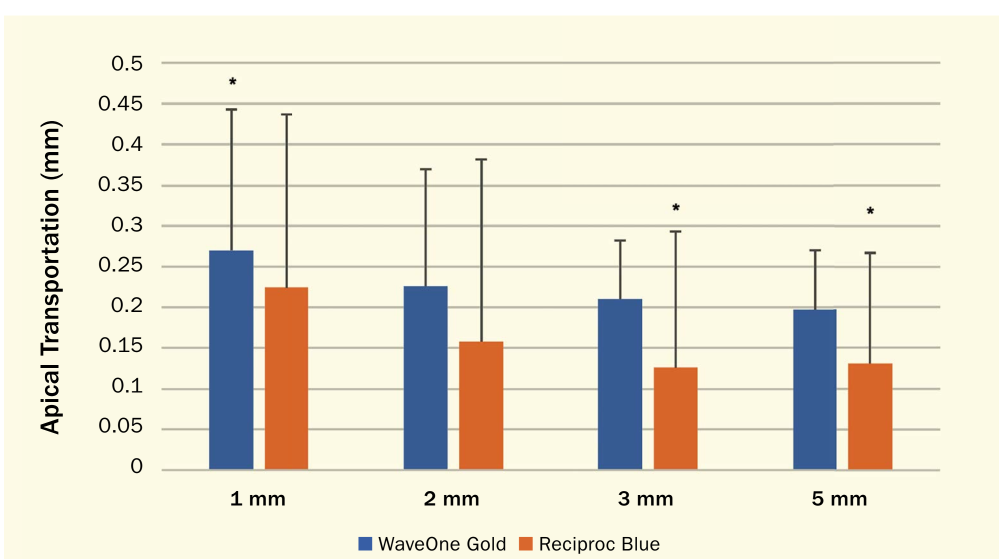

Figure 3
Graphic representation of apical transportation mean values (mm).
**Over bars indicate a statistically significant difference (the Kruskal-Wallis and Dunn's multiple comparison tests, p<0.05).*

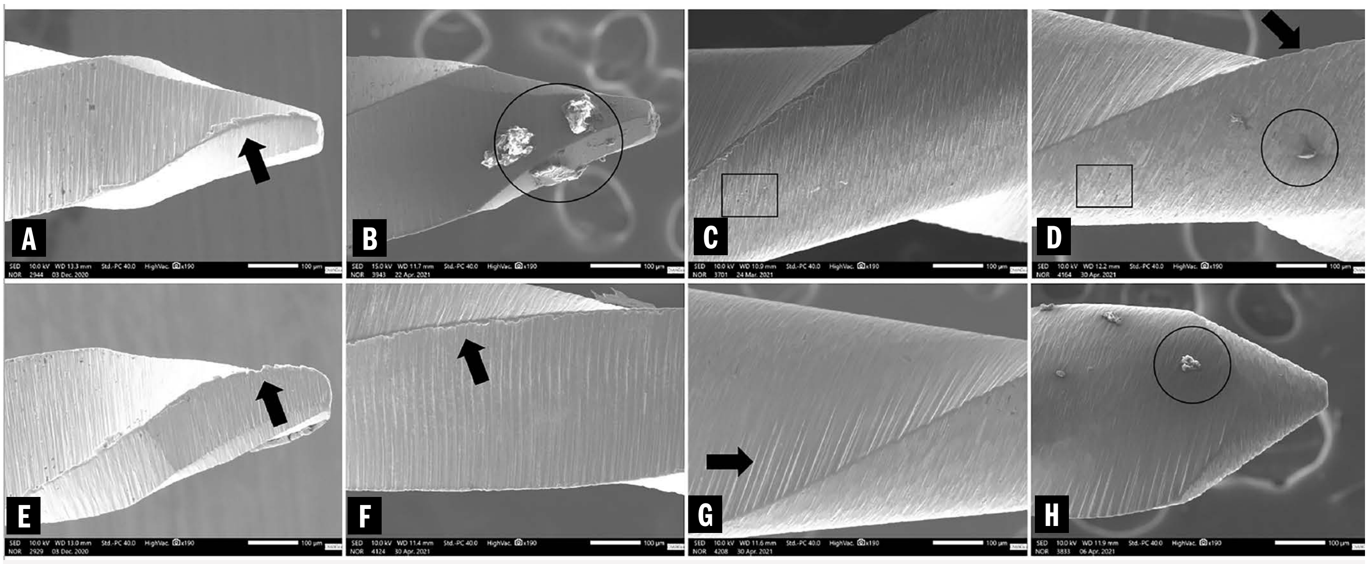

Figure 4
Representative SEM images of the active part of the instruments before and after continuous use. **A)** An irregular edge-like defect on the tip of the WaveOne Gold instrument before use (arrow), **(B)**, and after the second use. Note the presence of attached debris on the tip of the instrument (circle). **C)** Microcavities were observed in the Reciproc Blue instrument after the first and **(D)** third use (boxes). It is also possible to observe the presence of attached debris (circle) and irregular edge (arrow). **E)** A burr-like defect on the tip of the WaveOne Gold instrument after the first use and **(F)** after the third use (arrows). **G)** Perpendicular marks of the machining process (grooves) on the surface of the WaveOne Gold instrument before use (arrow). **H)** Attached debris on the Reciproc Blue instrument after the second use. (SEM×190).

test, $p>0.05$) and homogeneity of variance (The Levene test, $p>0.05$). The Kruskal-Wallis test for the independent factors, apical distance, and instrumentation system, was initially applied to the data, complemented by Dunn's multiple comparison tests ($p<0.05$). For the surface characteristics changes in the instruments, the Kruskal-Wallis test ($p<0.05$) was also performed. Statistically difference between groups was considered when $p<0.05$.

Results

Apical Transportation
The mean values (mm) for apical transportation (Figure 3). In general, WaveOne Gold and Reciproc Blue systems had similar apical transportation values, with no significant difference ($p>0.05$). However, when the apical distance was considered, WaveOne Gold at the 1st mm had greater apical transportation than Reciproc Blue at the 3rd and 5th mm ($p<0.001$).
Regarding the direction of apical transportation, both instrumentation systems had a greater tendency towards transport to the inner surface of the simulated root canal than towards the outer surface.

Analysis of Defects and Deformations on Instruments Surfaces
Representative SEM images of the active part of the instruments may be seen in (Figure 4). The incidence of defects and deformations (irregular edges, grooves, microcavities, burrs, and attached debris) observed on the instrument's surface before and after continuous use is in (Figure 5).
There were defects and deformations in all instruments, before and after continuous use (endodontic reintervention). WaveOne Gold always had a higher prevalence of irregular edge defects. On the other hand, there was a decrease in this type of defect according to the continuous use of instruments from both systems. Grooves were observed in the active part of the instruments after endodontic reintervention. However, when the times of use were compared, WaveOne Gold had a greater number of grooves after the second use. Conversely, Reciproc Blue had a greater amount of this defect after the first use.

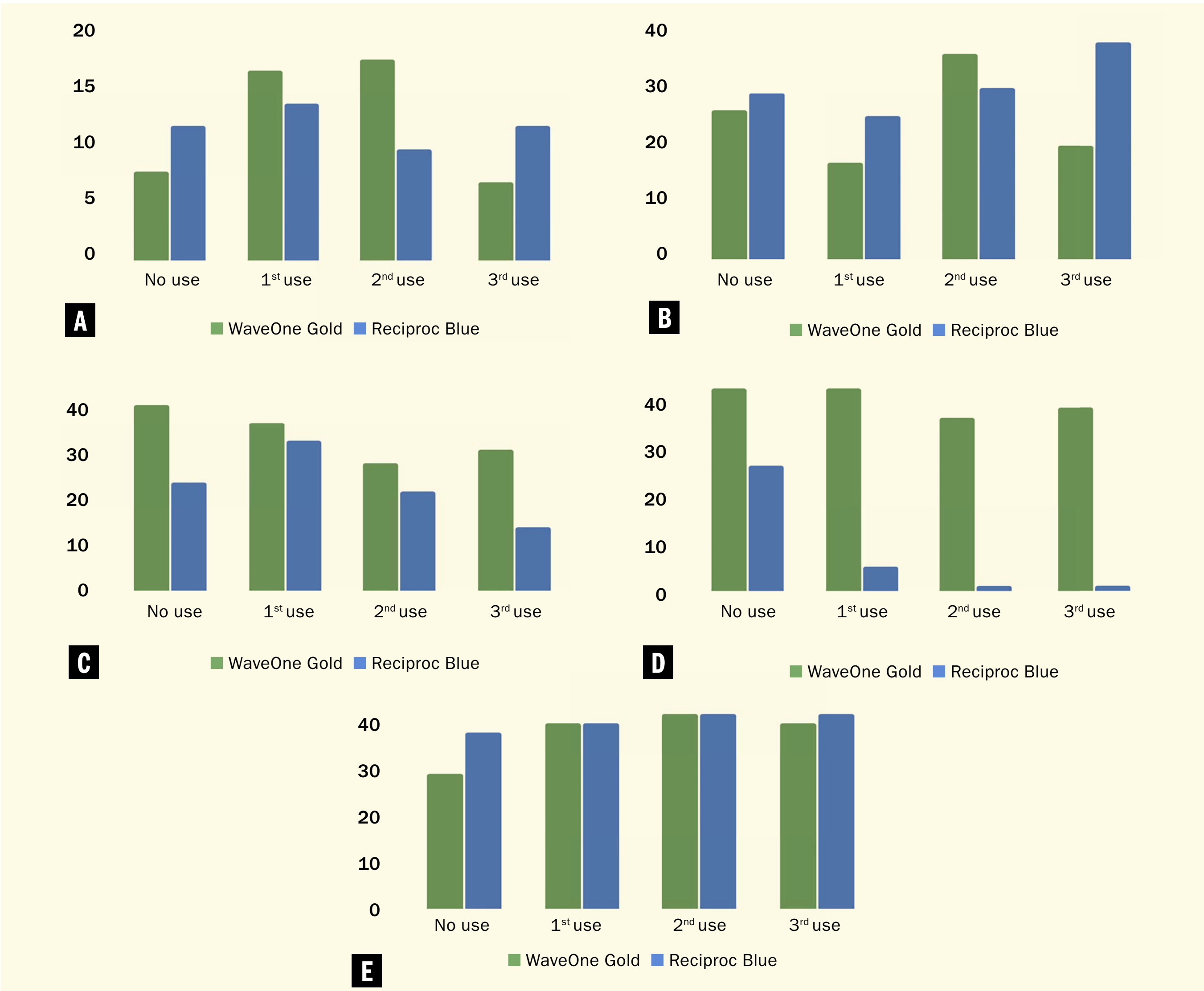

Figure 5
Incidence of defects on instrument surfaces before and after continuous use at the instrument tip, 2 mm, and 4 mm short of the instrument tip. **A)** Grooves. **B)** microcavities, **C)** irregular edges, **D)** burrs, **E)** attached debris (SEM×190).

Regarding the presence of microcavities, Reciproc Blue presented this defect even before the first use, which increased after the first and third use. WaveOne Gold presented this defect only after its second use. The same was observed for the presence of burrs in the active part of the instruments. Reciproc Blue presented this defect before the first use, increasing its prevalence after continuous use. The number of burrs observed in WaveOne Gold was smaller than in Reciproc Blue. At all periods of analysis, the presence of debris attached to the active part of both instrumentation systems was observed. For the WaveOne Gold, the amount of this defect was lower in comparison with the Reciproc Blue.

The results of the topographic changes on the instrument's surface, according to the scoring system used, are in (Figure 6). Reciproc Blue had a statistically significant increase in the number of defects and deformations after the third use ($p<0.001$). WaveOne Gold with no use and after the first use had a higher number of defects and deformations than Reciproc Blue with no use and after two uses ($p<0.001$). After the second use, WaveOne Gold had a higher number of defects and deformations than Reciproc Blue with no use and after two uses ($p<0.001$).

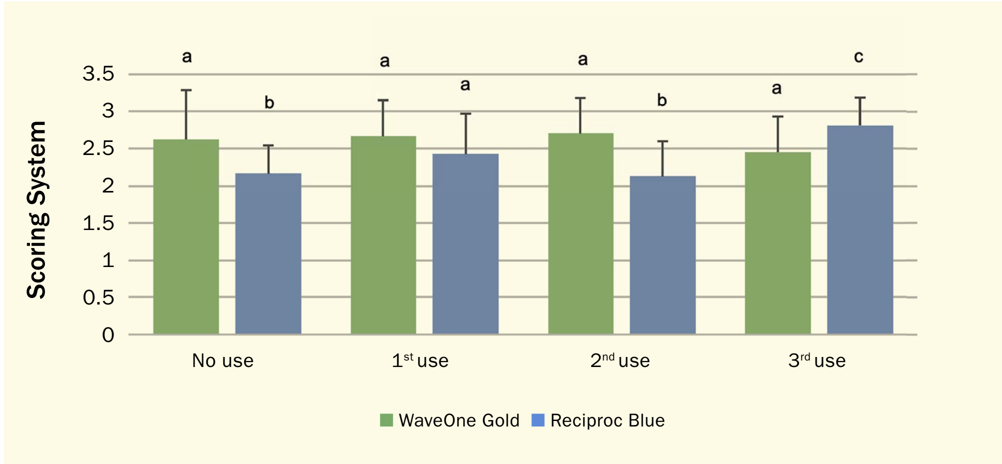

Figure 6
Graphic representation of mean scores of the defects observed on the instrument's surface before and after continuous use. Different lowercase letters over bars indicate a statistically significant difference (the Kruskal-Wallis test, $p<0.05$).

Discussion

The present *in vitro* study evaluated the apical transportation promoted by two thermally-treated reciprocating instruments, WaveOne Gold and Reciproc Blue, during endodontic reintervention. The change in the surface characteristics of these instruments after their continuous use was also evaluated. Based on the results obtained, the first null hypothesis was accepted, since both systems provided similar apical transportation. The second null hypothesis tested was rejected, as the instruments had significant changes in their surface characteristics after endodontic reintervention.

This laboratory study is the first to evaluate the performance of WaveOne Gold and Reciproc Blue instrumentation systems during endodontic reintervention. According to their manufacturers, both systems must be used to prepare three to four root canals in the same patient. Therefore, the present research aimed to mimic a clinical scenario in which the shaping ability and the changes in surface characteristics of these instruments were assessed after endodontic reintervention of a molar tooth containing three root canals. The maintenance of the anatomical path of the root canal plays a key role in the success of endodontic treatment, especially in root canals with accentuated curvatures.

Human teeth are widely used to perform dental research (19-21). Conversely, obtaining a great number of human teeth in proper conditions for laboratory use is a hard-to-reach condition, especially because of the ethical concerns involved (19-21). Therefore, finding a proper substitute for human teeth is crucial to conduct clinical-relevant studies (19-21). Despite the inherent limitations of an in vitro study, the use of resin blocks containing simulated root canals and superimposition of images before and after instrumentation is a widely accepted method for assessing apical transportation (19-21). The main advantage of this method is sample standardization (19, 22). Other methods can evaluate the root canal morphology in 3-D, such as cone beam computed tomography and micro-CT (13, 23). However, in these methodologies, large amounts of human teeth are required for pairing and standardization of the final sample, in addition to the high cost of the equipment. Thus, such methodologies reinforce the need for reliable human teeth substitutes, such as the resin block containing simulated root canals.

To avoid the accumulation of acrylic resin debris inside the simulated canals, copious irrigation with NaOCl solution was performed during instrumentation, filling material removal, and re-instrumentation of the canals. In addition, constant irrigation reduced the heat generated by the friction of the instruments against the resin walls of the simulated canal (20). The heat produced in the simulated canal by the action of the instruments may lead to softening of the resin, followed by cutting blade binding in the canal walls and separation of the instrument (20). In the present study, no instrument was fractured during the endodontic reintervention. To measure the apical transportation after endodontic reintervention, four reference points were established, corresponding to the 1st, 2nd, 3rd, and 5th millimetres below the root apex. Our results showed that no instrumentation system was able to maintain the original trajectory of the simulated root canal, causing minimal transportation at the different levels (apical distance), corroborating the studies by Orel et al. (19) and de Silva et al. (21).

Regardless of the apical distance, there was no statistically significant difference between WaveOne Gold and Reciproc Blue system regarding the apical transportation produced after the endodontic reintervention. These results agree with other studies that have shown that both instrumentation systems have similar shaping abilities (24, 25). On the other hand, Orel et al. (19) have reported that WaveOne Gold produced lesser apical transportation than Reciproc Blue. According to these authors (19), this fact may be associated with a greater centring ability of this instrumentation system when compared to Reciproc Blue. The ability of an instrument in remaining at the centre of the root canal space plays a key role in the proper shaping of the root canal (26). Conversely, when the apical distance was considered in the analysis, WaveOne Gold at the 1st mm had greater apical transportation than Reciproc Blue at the 3rd and 5th mm.

Regarding the amount of resin removed from the interior and/or exterior walls of the resin blocks, both instrumentation systems tend to cut more on the inner wall of the simulated root canals. However, it is worth noting that, on average, the apical transportation promoted by WaveOne Gold and Reciproc Blue was not greater than 0.3 mm. From a clinical point of view, such apical transportation value is considered acceptable, with a favourable prognosis (25, 27).

Furthermore, it is important to emphasize that in all the studies cited above, apical transportation was assessed post-root canal preparation and not post-endodontic reintervention, in which the filling material removal and root canal re-instrumentation are necessary. This experimental condition proves the novelty of the present research and the importance of its findings.

Besides the shaping ability analysis, in the present study, changes in the topography and surface characteristics of the instruments were assessed under SEM after their continuous use. Studies demonstrated SEM accuracy in assessing possible changes on the surface of metallic materials, such as endodontic instruments (14, 15). WaveOne Gold showed defects and deformations even before being used. Conversely, for the Reciproc Blue instrumentation system, the changes in its surface characteristics were more evident only after the third use. Despite these differences, this fact did not correlate with apical transportation since both systems had similar shaping abilities.

Thermally treated Ni-Ti instrumentation systems had phase transformation changes to increase their physical properties (martensitic instruments), such as flexibility and mechanical resistance (28, 29). According to Keskin et al. (29), Reciproc Blue has greater cyclic fatigue resistance than WaveOne Gold. This difference may be associated with the instrument manufacturing process (29). The Reciproc Blue instruments are manufactured from a Ni-Ti alloy coated by an oxide layer using a thermomechanical process (29). WaveOne Gold is manufactured from Gold-wire because of an advanced metallurgical process followed by heating, which produces instruments with high ductility (29). Despite being considered martensitic instruments, with high flexibility, Martins et al. (30) have reported these differences in the phase transformation temperatures for WaveOne Gold and Reciproc Blue systems. However, in their study, the fracture resistance of both systems was similar. The instruments used in the present study were brand new. However, several defects were observed along their active part even before use, especially for the WaveOne Gold system. The metallurgical process to fabricate the instruments may lead to a concentration of debris along their surfaces (15, 16). The presence of this debris even before use may lead to a faster surface deterioration when instruments are submitted to high levels of stress, as during endodontic reintervention (16). This phenomenon was observed for the WaveOne Gold instrument, as the continuous use produced an increase in surface defects for the Reciproc Blue instrument only after its third use. Although the amount of remaining filling material attached to the artificial canal after endodontic reintervention was not assessed in the present study, it is valid to emphasize that no instrumentation system is capable of entirely eliminating the obturation (2-5, 31). The remaining filling material may serve as a potential reservoir for microorganisms, thereby compromising the efficacy of non-surgical endodontic reintervention (1). Consequently, the utilization of instruments with greater taper should be considered for the removal of filling material, followed by root canal re-instrumentation, to achieve maximal removal of the filling material (16). Therefore, in this study, such therapeutic approach was addressed.

Conclusions

Despite the limitations of a laboratory study, it may be drawn that WaveOne Gold and Reciproc Blue systems provided minimal and similar apical transportation. SEM analysis showed defects on the instruments' surface of both systems even before use. However, the number of defects was greater for the WaveOne Gold system, which increased after continuous use. For the Reciproc Blue instrument, the number of defects increased only after the third use. It is licit to state that further studies are needed to better understand the mechanical and metallurgical behaviour of these instrumentation systems during endodontic reintervention.

Clinical Relevance

The research contributes to the evolution of endodontic reintervention protocols.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

Acknowledgments

None.

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