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Department I

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DOCTORAL THESIS

EVALUATION AND MONITORING OF ENDODONTIC PREPARATIONS WITH DEDICATED SYSTEMS

– A B S T R A C T –

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INTRODUCTION

In recent years, Endodontics, as a specialty of dentistry, has experienced a significant development both in terms of diagnostic methods and investigation of the endodontic anatomy, as well as in terms of the actual steps of treatment.

The increased use of computed tomographic examination to assess the difficulty of a clinical case, the use of magnification systems and especially of the endodontic operating microscope in all clinical steps of the treatment, the continuous development of the cross-section, tapers, and characteristics of the NiTi instruments, and the continuous improvement of the NiTi alloys, have significantly increased the predictability of the endodontic treatment.

The pre- and post-operative evaluation of the root canal anatomy can now be performed with the help of modern imagistic technologies, which allow clinicians to obtain a detailed image of the root canal, a thorough investigation of the way the instruments shaped and respected in preparation the original endodontic anatomy, to follow up the evolution of a treated case over time, and to evaluate the healing in cases of lesions of endodontic origin.

With the development of mechanized instruments for root canal preparation, facilitated by the continuous evolution of the nickel-titanium alloys, along with the modifications in their cross-section and tapers, endodontic treatment has experienced a significant improvement. This advancement has led to qualitative enhancements and reduced treatment time, resulting in better, safer, and faster outcomes in the benefit of the patient.

As a young clinician who uses various nickel-titanium shaping systems in my endodontic daily practice, my ongoing concern was to comparatively evaluate how different types of systems perform in the root canal preparation. My goal has been to highlight their level of fidelity in respecting the curvatures of the root canals and to analyze if they respect the original trajectory during shaping, or they induce deviations and alterations of the root canals, phenomenon known in endodontics as canal transportation.

Therefore, my doctoral thesis primarily focused on the comparative research of the efficiency in root canal preparation of three modern NiTi endodontic systems, which are widely used in clinical practice today, employing modern investigation techniques: CBCT examination and the photographic method.

This topic falls within the ongoing concerns of the developers of endodontic systems, clinicians, and researchers worldwide who aim to find a shaping system that, through its properties, ensures the best shape of the root canal preparation while maintaining the original anatomy, and preserving the maximum amount of dental structure from the root canal walls.

The increasingly frequent use of 3D printers in scientific research has been highly beneficial. This advancement has allowed for the easy printing of 3D-models that accurately reproduce the morphology of human teeth and endodontic anatomy. These models, made from resin materials with radiographic visibility, enable convenient investigations of the canal trajectory before and after root canal preparation.

Thus, the quality of comparative statistical analyses conducted, after eliminating inconsistencies arising from the varying hardness of human dentin, differences in root canal pathways, and different degrees of curvatures between two extracted tooth specimens, allows for obtaining much more accurate results in comparing the shaping systems used in the present doctoral thesis.

The analysis of the resulting preparations through cone beam computed tomography (CBCT), which allows for precise measurements through accurate digitized software programs, as well as the standardized photographic method using transparent resin blocks containing simulated canal replicas, adheres to modern protocols of analysis and measurement used in contemporary endodontic scientific research.

The research conducted within the thesis aims to evaluate the efficiency and accuracy of mechanical preparation of the root canal using three types of NiTi preparation systems. This was achieved by utilizing plastic blocks with simulated curved canals and 3D-printed replicas of human teeth, with specific research objectives regarding the internal or external transportation of the root canal, the instruments' centering ability, the apical transportation, the analysis of curvatures' angle variation, and the phenomenon of root canal straightening.

The objectives of the scientific research in this thesis were structured into the following stages:

1. Placing the research topic within the current general context of root canal preparation and establishing the specific methodology for each experimental study in line with the latest research in the field.

2. Selection and preparation of tooth replica samples, with curved simulated canals replicas, with three different rotary systems, and the comparative photographic documentation of the final preparations in relation to the initial trajectories of the root canals from four aspects (front, back, left, right).

3. Comparative evaluation of the root canal trajectoryafter shaping and its comparison with the initial one, analyzing the phenomena of internal-external transportation along the entire course of the root canal, highlighting the apical transportation phenomenon, and ensuring the proper positioning of the apical foramen on the captured photographs. Additionally, statistical analysis of the recorded data was performed.

4. Comparative evaluation of the efficiency in preparation of the three systems used through comparative statistical analysis at each third of the root canal (apical, middle, coronal) and overall analysis throughout the entire course of the root canal.

5. Analysis of instrument centering ability and comparative evaluation through statistical analyses; comparison of the results obtained with different types of instruments based on alloy type (blue or gold), cutting cross-section, diameter, taper, and type of motion used (rotation or reciprocation).

6. Printing 3D replicas of human single-rooted teeth with medium curvatures and selecting the optimal variant in terms of root canal trajectory and radiopacity, to be used in computerized tomography imaging analysis.

7. Comparative analysis through digital measurements on CBCT to assess the efficiency of the used systems in preparation on the 3D printed replicas.

8. Analysis of the variation in curvature angle of the root canal using different preparation systems on both types of used samples, through measurements performed on CBCT and digitally processed photographs.

9. Publishing the results of the scientific research.

10. Drawing final conclusions regarding the efficiency of the used shaping systems to establish optimal clinical protocols, aimed to increase the predictability and quality of the primary endodontic treatment.

The GENERAL PART is structured in two main chapters presenting the current state of knowledge in the field and places the research topics chosen in the experimental part of the thesis in the context of current endodontic research.

The first chapter, entitled *Principles, Techniques, and Instruments of Root Canal Preparation*, refers to the mechanical preparation of the root canals- the step of shaping, as one of the most important steps in endodontic therapy. It describes the two primary factors that significantly influence the root canal preparation: the initial endodontic anatomy, known as the canal factor, and the type of instruments chosen for shaping, known as the instrument factor.

It is highlighted that by using nickel-titanium alloy instruments (NiTi) at this stage, the resulted preparations are as close as possible to the ideal, more faithfully respecting the complex and multiple anatomical curvatures of the root canals, thus reducing the risks of possible iatrogenic errors, represented by deviations or alterations of the original path of the root canal.

In the present doctoral thesis, out of the various NiTi shaping systems available on the market, three of the most modern ones have been thoroughly analyzed and described for clinical use. These systems are as follows:

- the WaveOne Gold system: instrument Primary, with a tip diameter of 0.25 mm and an apical taper of 7%.

- the ProTaper Gold system: instrument F2, with a tip diameter of 0.25 mm and an apical taper of 8%.

- the Reciproc Blue system: instrument Reciproc Blue Red 25, with a tip diameter of 0.25 mm and an apical taper of 8%.

The use of instruments with similar apical dimensions, tapers and increased flexibility made from heat-treated NiTi alloys, has contributed to the enhancement of the statistical analysis quality within the experimental studies in the specific part of the thesis.

Chapter 2 of the General Part, titled *Evaluation Methods for Root Canal Instrumentation*, is structured into three subchapters aimed to describe the types of experimental models that can be used in scientific research on root canal preparation, the types of analysis that can be performed to assess the quality of these preparations, and the research methods used to evaluate the action of endodontic instruments inside the root canal.

The experimental models described in the first subchapter can be represented by extracted human teeth, 3D-printed replicas of human teeth, and transparent resin blocks containing simulated root canals with different degrees of curvature. As previously mentioned, to eliminate the variables represented by human teeth in the conducted studies, the scientific research in this thesis utilized the latter two options: 3D- printed dental replicas of permanent mono-radicular human teeth with moderate curvatures and simulated canals in plastic blocks, with increased curvatures.

The second subchapter presents the types of analysis for endodontic preparations, such as investigations regarding root canal transportation (deviation from the initial trajectory of the root canal due to preparation), analysis of the prepared and unprepared areas of the root canal, and changes in the curvature angles of the canal.

The third subchapter describes the methods for evaluating and conducting comparative analysis of endodontic preparations. In endodontics, two major aspects are pursued in experimental studies: the cleaning capacity of endodontic instruments and their ability to follow the initial trajectory of the root canal.

Studies that assess the cleaning capacity of the endodontic instrument evaluate the amount of debris generated during instrumentation on canal walls and analyze the percentage of un-shaped areas over the root canal walls. Clearly, in the cleaning process, irrigation protocols and solutions used play a crucial role. The main technique described for evaluating root canal cleaning is scanning electron microscopy (SEM).

The methods for evaluating the preparation capacity of endodontic instruments compare the post-operative root canal shape with the initial shape, aiming to assess the taper of the preparation, its diameters at different levels, and the ability of the instruments used in the study to remain centered within the canal and preserve as much of its original shape as possible. These methods also focus on ensuring that the original

trajectory and anatomy of the instrumented tooth are respected, with minimal transportation phenomenon.

The techniques used to evaluate the preparation capacity of endodontic instruments include digital radiography, standardized photography, cone beam computed tomography (CBCT), micro-computed tomography (Micro-CT/µCT), optical coherence tomography (OCT), finite element analysis (FEA), among others. In the present thesis, the methods of investigation utilized are cone beam computed tomography (CBCT) and the analysis of images resulting from standardized photography of the samples included in the studies.

The SPECIAL PART is structured into three chapters and includes three studies that aimed to evaluate the shaping capacity of the chosen endodontic NiTi instruments.

The first study, titled *"Comparative Experimental Study on the Efficiency of Three endodontic systems made of Nickel-Titanium alloys on Resin Blocks with Simulated Canals,"* presented in Chapter 3 of the thesis, aimed to comparatively evaluate the efficiency of instrumentation of simulated curved root canals in transparent resin blocks. The study utilized two reciprocating motion systems, Reciproc Blue and WaveOne Gold, and one continuous rotation system, ProTaper Gold. The study evaluated the capacity of each system to remove resin from the internal and external walls of the curvature, the total amount of resin removed, analyzed in each corresponding third of the root canal (apical, middle, and coronal), and the analysis along the entire length of the root canal. Additionally, the study analyzed the predominant direction of root canal transportation and the instruments' ability to achieve centered preparation.

For this study, 36 resin blocks with identical simulated canals were used, each with a curvature of approximately 40 degrees located in the apical third of the root canal. The blocks were divided into 3 groups, based on the system used for the preparation stage, with each group consisting of an equal number of 12 blocks (n=12).

Each plastic block was photographed in a standardized manner from four perspectives: anterior, posterior, lateral with the curvature oriented to the left, and lateral with the curvature oriented to the right, in the same fixed position relative to the digital camera, both before and after preparation. In each group, the four faces of the block were labeled as Left (L), Right (R), Front (F), and Back (B). Prior to taking the photographs, each resin block was injected with Castellucci solution to enhance the visibility of the root canal trajectory.

The shaping of all plastic blocks was performed by the same operator, following the same protocol, to eliminate variables introduced by operators with different levels of experience in using the tested instruments.

Prior to the actual preparation stage, the working length of each canal was determined using an ISO 10 K-file and an endodontic ruler. For the preparation stage, an X-Smart Plus endodontic motor from Dentsply-Maillefer, Ballaigues, Switzerland, was used, with the corresponding preparation instrument attached, maintaining a diameter of 0.25mm at the apical level of the preparation. The irrigation protocol included 5.25% NaOCl solution 1:1 (Cerkamed, Stalowa Wola, Poland), using dedicated irrigation syringes equipped with a luer-lock system and 23G irrigation needles.

The images obtained before and after the preparation stage were imported onto a desktop and processed using the computer program Adobe Photoshop CC (Adobe Systems Inc., San Jose, CA, USA). The Measuring Tool function in Adobe Photoshop CC was used to measure variations in distances in millimeters by overlaying the initial and final images of each plastic block. Differences between the initial root canal morphology and the morphology obtained after the preparation stage were evaluated. Measurements were taken at 12 different levels (13 measurement points) at 1mm intervals for the images from the lateral perspective, and at 10 levels for the anterior and posterior images.

The differences between the distances measured from the edge of the canal to the edge of the plastic block before and after the preparation represented the amount of resin removed by the chosen system, thereby quantifying the transportation of the root canal and determining the direction of deviation. The ratio between this difference and the width of the canal represented its centering ability. The measured values were statistically analyzed for each third of the root canal in all perspectives and globally along the entire length of the canal.

All the data were recorded in a Microsoft Excel file. Statistical analysis of the data was performed using the SPSS 22.0 software (SPSS Inc., Chicago, IL, USA). Each set of measurements was analyzed using the Kolmogorov-Smirnov test for normality. The level of statistical significance was set at $p<0.05$. Descriptive statistics (mean and standard deviation) were calculated for all data sets. To ensure a fair comparison between the data sets, an ANOVA test was conducted. The Tukey post hoc test was performed to determine the exact locations of the differences between groups.

Similar results were obtained at the statistical analysis conducted for each perspective investigated, showing that the WaveOne Gold and the ProTaper Gold systems removed more resin from the internal wall of the simulated canal, while Reciproc Blue removed more resin from the external wall, particularly in the apical third.

Statistically significant differences were observed in the coronal and middle thirds of the root canal, but not in the apical third. This suggests that all three systems tend to prepare the apical third in a similar manner. It was also noted that there were no significant differences in the preparation capacity between WaveOne Gold (WOG) and ProTaper Gold (PTG). Additionally, none of the three systems exhibited the same

preparation capacity along the entire length of the simulated root canal. No instrument used in the study fractured or became stuck in the root canal during the preparation of the samples.

The present study confirmed the usefulness of the resin blocks with simulated root canals and standardized photography methods for obtaining more accurate results in the conducted research.

In the second study, described in Chapter 4 and titled *"Experimental study on the Evaluation of Endodontic Preparations on 3D- Printed Dental Replicas with Standardized Curved Canals using CBCT Imaging method*," the changes in the root canal trajectory after preparation with the three systems compared in the first study were evaluated. This time, human single-rooted tooth replicas, 3D printed from radiopaque resin, were used to allow for their radiological investigation through 3D analysis using CBCT examination.

After successfully printing the dental replicas that corresponded to a visible root canal diameter on CBCT examination throughout its entire length, 60 dental replicas were fabricated for analysis. These replicas were divided into three groups.

Each replica underwent a CBCT examination before and after root canal instrumentation, using once again the Reciproc Blue, WaveOne Gold, and ProTaper Gold instruments, with each group consisting of 20 samples.

The CBCT images obtained before and after preparation were analyzed for the following parameters:

- Mesio-distal and bucco-lingual deviations from the canal trajectory after preparation

- The centering capacity of the instruments (ability to remain centered in the root canals) measured at 3, 6, and 9 mm from the most apical point of the canal

The evaluation of the CBCT images to determine the instruments' centering ability and the degree of root canal transportation was performed using the method described by Gambill et al., following the following formulas:

$|(M1 - M2) - (D1 - D2)|$ for the mesio-distal direction

$|(V1 - V2) - (L1 - L2)|$ for the bucco-lingual direction

The mean centered preparation, which represents the instruments' ability to maintain a centered position within the root canal, was analyzed using the following formulas: $|(M1 - M2) / (D1 - D2)|$ for the mesio-distal direction $|(V1 - V2) / (L1 - L2)|$ for the bucco-lingual direction

The fraction with the smallest value was selected for statistical analysis. The mean centered preparation reflects the instruments' ability to maintain a centered position within the canal, where a value of 1 represents complete centering, while other values indicate modifications to the canal's trajectory, indicating the occurrence of transport phenomenon induced by the preparation instruments.

(, where M1, M2, V1, V2, D1, D2, and L1, L2 represent the final and initial distances from the corresponding edge of the root canal to the root surface in the mesial M, vestibular V, distal D, and lingual L directions).

In the present study, all the systems induced minor root canal transportation, and none of the instruments had the ability to achieve perfectly centered root canal preparations.

Concluding that:

1. The Reciproc Blue instrument resulted in a more pronounced transportation of the root canal towards the mesial and buccal directions compared to the WaveOne Gold Primary and ProTaper Gold instruments of the same size and taper.

2. The centric preparation capacity was lower for the WaveOne Gold instrument in the mesio-distal direction and for the Reciproc Blue instrument in the bucco-lingual direction

3. The ProTaper Gold system exhibited a more anatomical pattern of root canal preparation, showing the most centered preparation capacity compared to the other evaluated systems, with minimal transport phenomenon induced.

The third study in the special part, described in Chapter 5, *"Experimental Study of Canals Curvature Angle Changes following Preparation with 3 Different Systems,"* aimed to evaluate the changes in root canal curvature resulting from mechanical preparation using the three systems compared in this thesis: ProTaper Gold, Reciproc Blue, and WaveOne Gold.

The variations in root canal curvature were analyzed after preparation with NiTi alloy instruments on all the 36 standardized plastic blocks used in the first study, through measurements taken from photographs, and on the radiographic images obtained from CBCT scans performed on the 60 3D-printed replicas of human single-rooted teeth.

For this study, digital images of standardized photographs were used, capturing the prepared plastic blocks from the lateral norm with the foramen oriented towards the right (R-right). The measurements of initial and final curvatures were conducted following the Schneider method on the imported photographs displayed on the computer screen. The method is like the original described examination, where the curvature angle is measured at the intersection of two lines-one connecting the root canal orifice with the starting point of the curvature, and the other connecting this point with the apical foramen. The curvature angle measurement was digitized using Adobe Photoshop software.

The analysis of the radiographic images obtained from the CBCT examination of the 60 printed dental replicas, which were securely fixed in an impression material to reproduce the same position, was conducted in a similar manner to the analysis on photographs. The same two lines were traced to obtain the curvature angle. Each study group included 20 replicas (n=20).

On the CBCT examination, the curvature angle was measured using the 3D OnDemand software (CELITEK), both before and after instrumentation. The variation in the curvature angle was represented, like the photographic analysis, by the difference between these two measured values. The means and standard deviations were calculated for each analyzed group, and the data were statistically analyzed to observe the differences between the tested systems.

In both studies included in this chapter, all compared instruments showed a minor decrease in the curvature angle of the root canal after instrumentation on each analyzed sample. The descriptive analysis on the replicas of simulated curved canals on plastic blocks showed an average variation of 1.93° in the curvature angle for ProTaper Gold, 2.49° for WaveOne Gold, and 3.33° for Reciproc Blue. It can be observed that Reciproc Blue induced the highest modification in the curvature angle compared to WaveOne Gold and ProTaper Gold, although there were no statistically significant differences between the three systems.

In the measurements performed on CBCT, the average variation was 0.95° for ProTaper Gold, 1.72° for WaveOne Gold, and 2.58° for Reciproc Blue 25. Therefore, once again, Reciproc Blue induced the greatest modification in the curvature angle compared to WaveOne Gold and ProTaper Gold.

Based on the results obtained in this study, the following conclusions can be drawn:

1. Reciproc Blue exhibited the highest tendency to straighten the curvature angle after the preparation of simulated root canals, while ProTaper Gold induced the least modification in the curvature angle, followed by WaveOne Gold. However, the observed differences were not statistically significant.
2. ProTaper Gold exhibited the least tendency to straighten the curvature of both simulated root canals and printed dental replicas, even though there were differences between the two types of samples in terms of the severity of curvature and the hardness of the material used
3. The gold alloy systems (WaveOne Gold and ProTaper Gold) proved greater flexibility and exhibited less straightening of the canal curvature after shaping, which could recommend them as more useful in clinical practice for preparing root canals with moderate to severe apical curvatures

As **final conclusion** of this doctoral thesis, it was observed that the gold alloy NiTi instruments provided a more predictable and accurate preparation of the root canals in all the conducted studies. These instruments demonstrated a better ability to maintain centricity within the canal, reduced apical transportation, preserved better the original canal curvature, and achieved a more conservative widening in the coronal and middle thirds of the root canal compared to the blue alloy instruments. However, at the apical level, both types of instruments performed similarly in terms of canal preparation.

Based on the overall length of the root canal, the systems showed statistically significant differences in their preparation capacity, leading to the conclusion that ProTaper Gold instruments followed by WaveOne Gold instruments demonstrated clear superiority over the Reciproc Blue system, specifically in terms of gold NiTi alloy compared to the blue alloy.

The contributions of this doctoral thesis are as follows:

-The chosen protocols in the experimental study, using photographic analysis from four different perspectives, allowed for a more precise monitoring of the endodontic preparations performed with the three evaluated systems compared to other studies in the field, which typically used photography from a single perspective.

-The precise measurements allowed for the identification of deviations in the preparation in both the mesio-distal and bucco-lingual directions, thus evaluating the phenomenon of transport induced by the instruments. Additionally, it facilitated the accurate analysis and description of the centering phenomenon relative to the axis of the root canal at each millimeter, each third, and overall, along the entire length of the root canal for each preparation system. This enabled a comprehensive comparison among the different preparation systems.

-The 3D printing of human tooth replicas using resin with sufficient radiopacity for analysis through CBCT, and the validation of printed samples through precise analysis and monitoring of endodontic preparations using dedicated software, paves the way for more frequent utilization of printed replicas in experimental studies with various applications in endodontics.

-The precise monitoring and description of the apical transport phenomenon and the variation of the curvature angle through two types of experimental studies, CBCT and digital photography, and computerized analysis of angle measurements on a significant number of samples with two types of curvatures (moderate and severe), have been achieved.

-The comparison of the shaping efficiency of three of the most modern systems made of heat-treated and controlled-memory nickel-titanium alloys, which utilize both rotation and reciprocation movements, places the thesis within the new research directions in modern endodontics.

The results of the experimental studies in this thesis can contribute to the development of clinical protocols that provide safety and predictability in current endodontic practice regarding the use of modern preparation systems made of nickel-titanium alloys. Furthermore, the publication of these research findings in high-impact journals and their numerous citations in other relevant articles validate the quality of the conducted studies.