Magnetic Resonance Imaging for Assessment of Endodontic Instruments' Precision during “L-Shaped” Model Root Canals Preparation

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Abstract: The purpose of the mechanical root canal preparation is to clean it and give it the right shape. The preparation should be carried out in a way that maintains the original curvature and initial orientation of the apical end. Insufficient root canal preparation may prevent effective chemical decontamination and obturation to the full working length. The study aims to evaluate the shaping ability and effectiveness of the NiTi rotary and reciprocating endodontic instruments, compared to standard hand files using magnetic resonance imaging based on spin echo. Material and methods: A comparative study of severely curved root canals’ shaping abilities using three NiTi systems and K-type hand files was performed, with 40 training “endo-blocks” presenting with “L-shaped” canal. The root canal topography and geometry “before” and “after” mechanical preparation obtained by the magnetic resonance imaging based on the spin echo was used. The main measurement was made using the RARE sequence, with slice thickness reduced to 100 micrometers. In order to improve the signal-to-noise ratio, NA = 25 was used. To minimize the measurement time, the field of view was limited to a cuboid 17 × 16 × 3 mm, with a resolution of 33 × 31 × 100 micrometers. Each 3D image consisted of 512 × 512 × 30 voxels. The imaging plane has been selected in such a way as to fully illustrate the course of curvature of the model root canal. For TR = 5 s and effective TE = 36 ms, TA was 1.5 h. Measurements were performed twice, before and after the preparation of endo-blocs with a selected type of endodontic tools. Results: The use of rotary NiTi instruments caused a substantial alteration in the curvature topography and angle of the canals and change in the curvature length. The substantial discrepancy was observed during the preparation of simulated root canals with the reciprocating instruments and the use of WaveOne files led to the largest volume variation. No dependence between the amount of material removed and the measured intracanal curvature length. The substantial discrepancy was observed during the preparation of simulated root canals with the reciprocating instruments and the use of WaveOne files led to the largest volume variation. No dependence between the amount of material removed and the measured intracanal curvature. Conclusions: All the studied endodontic instruments allow a safe preparation of curved root canals in simulating in vivo conditions. The abbreviation of original root canals topography does not seem to be significantly altered following mechanical preparation of simulated, severely curved root canals. The spin echo-based magnetic resonance imaging technique can be utilized for visualization of the internal topography of the root’s canals in vitro before and after their mechanical preparation in vitro conditions. In the future, magnetic resonance microscopy may become a diagnostic tool supporting the work of a clinician.

Keywords: root canal curvature; Schneider’s angle; root canal mechanical preparation; endodontic instruments; nitinol alloy; transportation; aberrations; magnetic resonance imaging
1. Introduction

The achievement of the success in endodontic treatment results from precision during both diagnostic and therapeutic procedures. Mechanical root preparation is one of the most important stages in root canal treatment. That particular stage influences the following procedures, such as chemical decontamination and three dimensional obturation, determining the final effect. The purpose of the mechanical canal preparation is to remove the vital or necrotic pulp from canals and shape to obtain conical shape with maintained original curvature and apical foramen location. The complete procedure should not be iatrogenic; perforations, instruments’ fracture and ledge formation should be avoided [1,2].

During canal shaping, regardless of the used technique, procedural mistakes may occur, such as deformations or changes of the primary canal shape, in the form of over-preparation of external canal wall in its apical part and not enough negotiation of coronal part. Removal of too much dentin in one canal region results in not enough mechanic preparation of the opposite part. The real thickness of the dentin must be taken into account while canal preparation in order to prevent overpreparation and root fracture. Not properly instrumented canal’s walls may result in the unsuccessful outcome of the root canal treatment [3,4].

Intense development of materials science in the second half of the 20th century has led to the invention of shape-memory alloys, since Buchler in 1962 invented the most known shape-memory alloy nickel-titanium (NiTi) known as NITINOL. NiTi alloys used in the manufacturing of endodontic instruments are characterized by superelasticity which means that they can be distorted and return to their pre-defined shape. This unique feature enables the preparation of curved canals with maintaining their natural shape [5–7]. The assessment of canal shaping and mechanical instrumentation using different endodontic instruments [8–10], in vast majority of studies was made on the basics of images taken before and after the preparation of training blocks or with the usage of volumetric tomography (3D) [11]. The magnetic resonance microscopy/imaging enables precise imaging and during the following years there appeared publications presenting attempts at using magnetic resonance microscopy to determine the geometry of the tooth surface, root canals, the location of cavities, and to compare tooth structure of younger and older patients. The techniques used for this type of imaging are generally referred to as spin echo and gradient echo methods and they facilitate the imaging of soft tissue or a hydrated medium [12–15]. Authors decided to use that method in the assessment of training blocks’ volumetric topography before and after their mechanical preparation.

Here, our study aimed to assess, in a comparative way, the preparation mode of simulated root canals with type L curvature negotiated with the rotary NiTi Mtwo and ProTaper Next instruments reciprocating WaveOne instruments vs. standard hand stainless steel K-files using magnetic resonance imaging based on spin echo.

2. Materials and Methods

The in vitro laboratory research was conducted in the Department of Conservative Dentistry with Endodontics of Silesian Medical University in Katowice and in Institute of Nuclear Physics, Polish Academy of Sciences in Cracow.

The research material consisted of 40 training blocks (Endo-Training Bloc®️, Dentsply/Maillefer, Ballaigues, Switzerland) made of epoxy resin, with “L-shaped” canals of size ISO 10 in the apical region and working length 16 mm were used in the research (due to producer) (Figure 1).

The initial length of the simulated root canal ranged from 16 to 17.75 mm, and the curvature angle (due to Schneider with own modification) was 42° to 52°. The training blocks were randomly divided into four groups (each group was composed of 10 blocks). Each block has been marked with its individual number and group name (related to the endodontic instrument applied to a particular group). Two different rotary tools (MT, PN), reciprocal tool (WO) and classic hand K file were used to elaborate the model canal in
the blocks’ corresponding groups. For simulated canals preparation of the rotary (MTwo, ProTaper Next), reciprocating (WaveOne), and hand K-file instruments were used.

![Image of a training block](image)

**Figure 1.** Example of resin-based endo-training block with “L-shaped” canal, before preparation by the rotary endodontic instrument (MTwo).

### 2.1. Magnetic Resonance Imaging (MRI)

The measurements were accomplished using preclinical Bruker Biospec 9.4 T MR scanner, equipped with gradient coils of 60 mm ID and the maximum field gradient of 1 T/m. The quadrature RF birdcage coil (35 mm ID) was used for collecting signals. Before insertion into the MRI probe-head, the root canal models were rinsed with distilled water using a syringe with a needle to avoid fine debris and micro-bubbles distorting the MR image. The training blocs were placed in a syringe with an inner diameter of 12.7 mm, filled with water. Prior to the experiment, the distilled water was degassed to uniformly fill the cavities of the endo-block with the liquid and minimize the occurrence of air microbubbles. This enabled eliminating sources of artefacts originating from the difference in magnetic susceptibility between air and water or endo-block material. After degassing, the container (syringe) in which the measurement was carried out was sealed with parafilm. RARE pulse sequence was used for a pilot image made up of 32 layers with a thickness of 500 micrometers and in-plane resolution of 31 × 31 micrometer. The image orientation was selected so that the plane of the layers was perpendicular to the upper edge of the training block, and the entire imaged area with a 16 × 16 × 16 mm field of vision included the syringe containing the interesting fragment of the model root canal. With repetition time (TR) of 5 s and 3 acquisitions (NA), the measurement time (TA) was 10 min. The obtained image allowed for positioning the imaging plane for the following high-resolution imaging, aimed at the accurate 3D mapping of the model root canals’ curvature details.

The main measurement was made using the RARE sequence, with slice thickness reduced to 100 micrometers. In order to improve the signal-to-noise ratio, NA = 25 was used. To minimize the measurement time, the field of view was limited to a cuboid 17 × 16 × 3 mm, with a resolution of 33 × 31 × 100 micrometers. Each 3D image consisted of 512 × 512 × 30 voxels. The imaging plane has been selected in such a way as to fully illustrate the course of curvature of the model root canal. For TR = 5 s and effective TE = 36 ms, TA was 1.5 h. Measurements were performed twice, before and after the preparation of training blocs with a selected type of endodontic tools.

**Imaging Data Analysis**

The obtained 3D imaging data were analyzed using Fiji [16]. First, the image was filtered using 3D median filter. This filter effectively eliminates noise without adding addi-
tional values to the image, allowing keeping sharp edges between water-filled model of root canal and the surrounding solid resin. Thus, the image was binarized based on signal threshold obtained from the histogram. The binarized 3D images, before and after the endodontic development, were subtracted and added to each other and differential/summed 3D images were constructed. Then, based on the number of voxels of the differential image, after taking into account the volume of a single voxel (i.e., $31 \times 33 \times 100$ micrometers), the volume difference was determined, corresponding to a volume of material removed during endodontic elaboration.

2.2. Training Blocks Preparation

After the images of the endo-training blocks were obtained, the procedure of mechanical canals’ preparation started. In order to mark the range of preparation K-file size 08 ISO (Poldent) was introduced to each canal. The instrument had a stopper for working length measurement. It was introduced to the canal with the clockwise motion (maximum range of motion-90°) until the instrument’s tip was visible in the apical foramen. The endodontic ruler was used (VDW) to measure the obtained length, then 0.5 mm was subtracted (as a medium distance between anatomic apex and physiological foramen in human teeth). Canals were instrumented with K-file, on the working length, till size 15 was reached.

MT group: Training epoxy resin blocks (n = 10) were instrumented with Mtwo (VDW) with the usage of single-length technique with a sequence of instruments: 10/04, 15/05, 20/06, 25/06 and endodontic micromotor X-Smart plus (Dentsply, Maillefer). The speed and torque were compatible with the producer’s recommendations.

PT group: 10 simulated canals were prepared with 17/04 (X1) and 25/06 (X2) ProTaper (Dentsply, Maillefer) files with the single-length technique. X-Smart Plus micro-motor (Dentsply, Maillefer) was used (speed: 300 rpm, torque recommended by instruments’ producer).

WO group: Ghassan Yared reciprocating technique of single instrument was used to prepare 10 training blocks. The procedure was done with the use of WaveOne Primary (Dentsply, Maillefer) file size 25/08, endodontic micro-motor X-Smart Plus (Dentsply, Maillefer) programmed as recommended by the producer.

K group: simulated canals were instrumented on the working length with K-files (Poldent) till size ISO 25 was reached. All instruments were introduced on the working length with clockwise motion (maximal range-90°).

After usage of each instrument, canal was rinsed with 2 mL of NaCl. The Luer-lock syringe with single lateral opening endodontic needle ($0.3 \times 25$ mm) was used. In order to remove rests of the resin, instruments were regularly cleaned. Before the next instrument use, the canal’s patency was checked with K-file size ISO 10 introduced to the full working length, additionally, an intracanal lubricant was used. When the simulated canals’ preparation procedure was completed, canals were dried with the paper points (Poldent) and the patency was checked again with K-file size ISO 10.

2.3. Working Length Alteration

The working length was checked and measured with the K-file size ISO 08 (Poldent). The instrument was inserted to the canal with the clockwise motion till its ending was visible in the apical foramen. The obtained length was measured with an endodontic ruler (VDW) then 0.5 mm was subtracted. The measurement was done with the Seliga Actus dental loupe (magnification $\times 2.5$ and accuracy 0.25 mm).

2.4. Volume Changes

Binary 3-dimensional images before and after canal preparation were subtracted from each other. Then, on the basics of voxel numbers of the differential image, after single voxel volume ($31 \times 33 \times 100$ $\mu$m) was taken into account; the volume was counted. In order to check how much resin was removed, parameterization was carried out as images of size $16,000 \times 17,008$ $\mu$m were obtained. The curve located in the canal center was
determined. Measure points were located 1 mm from each other, starting from the root apex. 10 measuring points were determined for each image.

2.5. The Amount of Removed Resin and Apex Transportation

The removed resin amount was counted by perpendicular measurement of the distance from the canal wall after its preparation to measurement point, separately for outer and inner canal wall. Transportation was assessed in the first measurement point by subtraction of the amount of removed resin from opposite canal wall. If the positive value was obtained it meant that the transportation was toward the external canal’s curvature wall, if negative—toward internal canal’s curvature.

2.6. Analysis of Curvature Parameters

Both curvature angle due to Schneider in own modification and curvature length (CL) was measured before and after instrumentation. In order to measure the curvature length, the following formula was used: \( CL = \frac{4\pi S}{360} \). Then the difference between obtained results was counted. If the negative value was obtained, it meant that the curvature angle increased, if positive—decreased (Figure 2).

![Figure 2. Curvature angle due to Schneider in own modification.](image)

2.7. Statistical Analysis

Quantitative data regarding parameters alterations of canals’ curvature, length of the curvature, the volume of the canal and the quantity of material gathered from each group fulfilled the assumptions of Shapiro–Wilk test which was the basis for the parametric tests (Statistica v10, SUM licence). The descriptive characteristic was presented as arithmetic average and standard deviation. The statistical analysis of the instruments’ influence on curvature angle, length, and volume was done using t-test for dependent samples, comparing the arithmetic averages obtained “before” with those “after.” In case of angle curvature measurements, it was checked with the usage of t-test for one sample if the results obtained before did not differ significantly from the assumed value 45. The comparison of effect of used instruments (MT, PN, WO, K) on the changes of measurements values was made with the ANOVA analysis. Multiple post hoc analysis was done with the NIR test. The part of the experiment regarding the measurement of the material removed by instruments was done in 10 measurement points (from left and right side of the point). For each of the point, the single factor analysis and NIR test were done. Tests regarding the arithmetic averages require fulfilling of the assumptions on the diversity of variances. Verification of that assumption was performed with Levene and Brown-Forsythe tests. The results were statistically significant if \( p \)-value was lower than 0.05.
3. Results

Visualization of the output data was obtained because of the strong contrast between the signal coming from the protons of water and the lack of signal from the training endo-blocks’ solid material. The water surrounding the endo-blocks’ outer surfaces and filling its interior (model canal) allows for exact representation of its shape. The MR image only shows the signal from the water, which results from the measurement allowing obtaining a “negative” three-dimensional numerical copy of the training endo-block. The longitudinal relaxation time $T_1$ for distilled water is about 3 s. This requires the application of a long repetition time in the measurement sequence and, as a result, increases the overall measurement time. On the other hand, the long transverse relaxation time $T_2$ of distilled water allows the use of multi-echo imaging sequences. By effectively using time between repetitions of the measurement sequence, allows obtaining a three-dimensional image with high resolution in a relatively short time. Figure 3 shows examples of a central slice of high-resolution MR images of the elaborated model root canal MT-2, and Figure 4 shows the binary 3D images, Figure 5 after subtraction (a) and addition (b) of the binary images before and after the endodontic preparation.

Figure 3. Central slices from the 3D MR images of MT-2 training endo-block before and after endodontic preparation.

Figure 4. Central slice from the binary 3D image of model root canal MT-2 before and after endodontic preparation.
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(a) (b)

(a) 
(b) 
K-2 
(a) 
(b) 
PN-1

Figure 5. Central slice from images obtained after subtraction (a) and addition (b) of the binary images before and after root canal preparation in particular groups.

3.1. Changes in Volume

Significant differences between blocks prepared with different endodontic tools are clearly visible. The volumes of model root canals before and after the mechanical preparation are presented in Table 1. Before endodontic preparation average canal volumes were found to be the same within each group. Preparation by endodontic tools, which removes part of the endo-block material, causes an increase in canal volume. The statistical analysis carried out showed that in each group, the average volume of the channel after the mechanical development differs significantly from the average volume before preparation. The difference is very highly statistically significant \((p < 0.0001)\). The lowest changes of volume were observed in K group and the highest in WO group. Results obtained in MT and PN groups showed no statistically significant differences. Average values obtained in K and WO groups were highly statistically significant than those obtained in other groups.

Table 1. Average volumes of the model root canal before and after elaboration with specific endodontic tools.

| Tool Type | Canal Volume \([\text{mm}^3]\) | Test \(t\) | \(p\) Relative Difference | ANOVA \(p\) | Test NIR \(p\) |
|-----------|----------------|---------|------------------------|-------------|----------|
| MT        | 1.03 ± 0.11 | ≤0.001  | 2.37 ± 0.22            | <0.0001     | ≤0.001   |
| WO        | 0.99 ± 0.13 | <0.001  | 3.30 ± 0.26            | <0.0001     | <0.001   |
| K         | 1.05 ± 0.10 | <0.001  | 0.25 ± 0.09             | <0.0001     | <0.001   |
| PN        | 1.00 ± 0.14 | <0.001  | 2.19 ± 0.32            | 0.1221      | <0.001   |

The least change in volume was found in the group K (on average 0.25 mm\(^3\)), while the largest in the group WO (on average 3.30 mm\(^3\)). The obtained results for the MT and PN (mean values 2.36 mm\(^3\) and 2.19 mm\(^3\)) were not statistically different from each other. The average volume change differed within a highly statistically significant level when compared K vs. WO groups.

3.2. The Amount of Removed Resin and Apex Transformation

Figure 6 shows dependence of the width of the removed material on the side of the canal curvature and the position along the canal. Besides the overall volume change, the local changes in canal shape after elaboration were analyzed. From visual observation of the differential or summed images the amount of the removed material is variable depending on the side of the canal curvature and the canals' topography. Generally, at the end of the canal there is a tendency to remove more materials from the outer part of the curvature, while in the central region the inner volume is more affected. It is understandable, as the endodontic tool, with certain stiffness, tends to eliminate the canal's curvature during the negotiation. Interestingly, significant differences between different type of
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| Tool Type | Canal Volume [mm$^3$] | Test t ($p$) | Relative Difference | ANOVA ($p$) | Test NIR ($p$) |
|-----------|------------------------|--------------|---------------------|-------------|---------------|
|           | before                 | after        |                     |             |               |
| MT        | 1.03 ± 0.11            | 3.39 ± 0.24  | <0.0001             | 2.37 ± 0.22 | ——            |
| WO        | 0.99 ± 0.13            | 4.29 ± 0.26  | <0.0001             | 3.30 ± 0.26 | <0.0001       |
| K         | 1.05 ± 0.10            | 1.30 ± 0.09  | <0.0001             | 0.25 ± 0.09 | <0.0001       |
| PN        | 1.00 ± 0.14            | 3.19 ± 0.35  | <0.0001             | 2.19 ± 0.32 | <0.0001       |

The least change in volume was found in the group K (on average 0.25 mm$^3$), while the largest in the group WO (on average 3.30 mm$^3$). The obtained results for the MT and PN (mean values 2.36 mm$^3$ and 2.19 mm$^3$) were not statistically different from each other. The average volume change differed within a highly statistically significant level when compared K vs. WO groups.

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3.3. Changes of Working Length

Statement of working length measurement before and after simulated canals preparation, proved that there were changes only in single cases (Table 2). The statistical analysis proved no statistically significant differences between groups, so the type of used instruments did not influence the working length changes.
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Figure 6. Amount of resin removed in particular measurement points in groups: (a) K, (b) MT, (c) PN, (d) WO.

Table 2. Comparison of working length changes.

| Endodontic Instrument Type | Working Length Changes (mm) |
|---------------------------|----------------------------|
|                           | Min | Max | Me  | Q₁  | Q₃  |
| K                         | 0.0000 | 0.2500 | 0.0000 | 0.0000 | 0.2500 |
| PN                        | 0.0000 | 0.5000 | 0.0000 | 0.0000 | 0.2500 |
| MT                        | 0.0000 | 0.5000 | 0.0000 | 0.0000 | 0.2500 |
| WO                        | 0.0000 | 0.5000 | 0.0000 | 0.0000 | 0.0000 |

*p = 0.9035.

3.4. Assessment of Canals’ Shape Changes after Instrumentation

The analysis of binarized images, showed changes in the canal’s shape in 50% of K group endo-blocks vs. 20% of MT, PN, and WO groups. Most frequently observed aberration was elbow-type root canal deformation. Perforations were not observed in any group. The statistical analysis proved that the frequency of ledges (*p* = 0.78360), elbows (*p* = 0.7114) and perforations is not dependent on the used instrument. The sum of the aberrations is also not dependent on the kind of used instrument (*p* = 0.3997).

3.5. Changes of Curvature

The average curvature angle as per Schneider’s classification in own modification before mechanical preparation did not significantly differ from 45°. The biggest average change in canals curvature was observed in WO group (7.0+/−2.87), the lowest in K group (1.30+/−1.49) (Table 3).

The data analysis proved that the average curvature angle before canal preparation is different from after it was instrumented in each group. Highly statistically significant differences were observed in WO, MT, and PM groups (*p* < 0.0001) while in K group statistically significant (*p* < 0.05) (Table 3). The NIR test showed a statistically significant difference in
changes of curvature angle only between WaveOne and Mtwo instruments. Comparison of rest of the examined instruments showed no statistically significant differences (Table 3).

Table 3. The mean (X) and standard deviation (SD) of angles’ curvature before and after their mechanical preparation, and the differences (after vs before).

| Endodontic Instrument Type | Angle’ Curvature before | Angle’ Curvature after | Test t (p) | Difference | ANOVA (p) | Test NIR (p) |
|---------------------------|-------------------------|------------------------|------------|------------|-----------|-------------|
| MT                        | 44.80 ± 0.42            | 50.10 ± 0.86           | <0.0001    | 5.30 ± 0.83| <0.0001   | 0.0460      |
| WO                        | 46.00 ± 33.00           | 53.00 ± 4.83           | <0.0001    | 7.00 ± 2.87| <0.0001   | 0.0460      |
| K                         | 45.30 ± 1.77            | 46.60 ± 2.84           | 0.0224     | 1.30 ± 1.49| <0.0001   | <0.0001     |
| PN                        | 45.10 ± 0.57            | 51.30 ± 1.42           | <0.0001    | 6.20 ± 1.55| <0.0001   | 0.2812      |

In each group, the average length of the canals’ curvature before the mechanical preparation is different from the one after the preparation. That difference is highly statistically significant (p < 0.05) (Table 4). Comparative analysis of the instruments showed statistically significant differences in curvature length changes only while comparing WO and MT groups.

Table 4. The mean (X) and standard deviation (SD) of angles’ curvature length before and after their mechanical preparation, and the differences (after-before).

| Endodontic Instrument Type | Angles’ Curvature Length before | Angles’ Curvature Length after | Test t (p) | Difference | ANOVA (p) | Test NIR (p) |
|---------------------------|---------------------------------|--------------------------------|------------|------------|-----------|-------------|
| MT                        | 1.56 ± 0.01                     | 1.75 ± 0.03                   | <0.0001    | 0.19 ± 0.03| <0.0001   | 0.0460      |
| WO                        | 1.61 ± 0.12                     | 1.85 ± 0.17                   | <0.0001    | 0.24 ± 0.10| <0.0001   | <0.0001     |
| K                         | 1.58 ± 0.06                     | 1.63 ± 0.10                   | 0.0224     | 0.05 ± 0.05| <0.0001   | <0.0001     |
| PN                        | 1.57 ± 0.02                     | 1.79 ± 0.04                   | <0.0001    | 0.22 ± 0.05| <0.0001   | 0.2812      |

3.6. Summing-Up of the Results
1. The use of rotary NiTi instruments caused a substantial alteration in the curvature topography, angle of the canals, and change in the curvature length.
2. The biggest discrepancy was observed during the preparation of simulated root canals with the reciprocating instruments and the use of WaveOne files led to the considerable volume variation.
3. No dependence between the amount of material removed and the measured intracanal side was observed when NiTi instruments were used.
4. Preparation with hand K-type files revealed a relationship between the measuring side and the amount of material removed, with the lower values obtained for the canals’ internal curvature.

4. Discussion
Simulated root canals in training endo-blocks are characterized by similar parameters. Therefore, it can be assumed that the experiment environment in which they are used provides uniform, reproducible features for a single operator. The only variable seems to be a type of the instrument used for canals’ preparation. However, the fact that endo-blocks are made of acrylic resin, this might be a limitation because material’s mechanical properties are different from those of dentin. As a result, it is speculated whether the obtained results could be also validated for clinical outcomes prognosis. Leski following Yo, described that while the canals are being prepared with the rotary instruments, the generated heat can result in resin softening and blocking of instruments’ cutting surfaces, subsequently leading to ineffective instrumentation [8]. However, Sonntag et al. obtained matched results in simulated endo-blocks also assessing the instruments interaction in human teeth [5]. Analyzing the advantages and disadvantages of utilizing training endo-blocks and natural hard tooth tissue, it is not recommended to classify the endo-blocks as
an optimal material for pre-clinical research regarding the comparative analysis of canals shaping with of endodontics instruments in vitro.

While for canal preparation comparison it is important to reach the same size at the apex [6]. In this research simulated canal was enlarged in the apical diameter to size ISO 25. The same value was set up in the experiments conducted by other authors [7,17]. None of the canals was blocked with the resin debris. Similarly, Yang et al., while assessing the possibility of molar teeth canals shaping with the usage of ProTaper and Hero Shaper, maintained the patency of all prepared canals regardless of the system used [3]. Yang et al. has also conducted the research on canal shaping with ProTaper and Hero 642 with the usage of training blocks. In that research, they also have not observed the obliteration of the canals [18]. Guelzow et al. comparing the efficiency of molar teeth’s canals preparation with the usage of 6 rotary systems and hand instruments have not observed any accidental canals’ obliteration with the dentin debris [10]. Patency was maintained while preparation was also confirmed by other authors [19].

The used instruments were remained intact during preparation as a result of usage of new set for only one simulated canal. Own results are coherent with the same as obtained by Romazani et al., who compared the molar teeth canals’ shaping with Mtwo, Reciproc, and K-files [4]. Narayan et al., who were preparing canals with rotary systems: K3, Mtwo, and Race, have not observed any separated files [20]. No deformation in files made of NiTi alloy was observed, however, it occurred in case of hand instruments. The frequency of deformation was rising with the instruments’ diameter in apex, which can be explained with lower flexibility of instruments and higher susceptibility to deformation. Similarly, both Łaszkiewicz et al. and Ramazoni et al. have not observed the instruments deformation, neither [4,21] Jardine et al. [22] detected a very little deformation on the surface of WaveOne and ProTaper Universal (SEM assessment).

In this study, the alterations of working length (WL), however not statistically significant, were observed. In the published research, the loss of WL was observed [3,7,8,18,23–25]. Some of these results has been reported as not statistically significant [3,5,10,24], in the contrary to others. [7,8,18,23]. No loss of WL was observed by Perez et al. and Kroczyńska et al. [19,26]. Łeski et al., who instrumented “L-shaped” simulated canals, observed change of WL in ProTaper Next estimated at 0.22+/−0.082 mm [8]. Those results were more considerable than in our study (0.125+/−0.20 mm). Wilkoński et al. observed bigger change in WL in WaveOne (0.47 mm) and smaller in Mtwo (0.04 mm) [17]. Kroprowicz et al. obtained lower WL loss in ProTaper Next than in WaveOne [25]. Radwański et al. obtained lower loss of WL while using with WaveOne Gold than in ProTaper Next. However, that loss was bigger than in own research [7].

In 5 out of 10 cases, while preparing the canal with hand K-files, elbow or ledge intracanal errors were created. Results obtained by Kroczyńska et al. in endo-blocks negotiated with K-files showed that elbow and ledge occurred in 4 out of 10 cases [26]. They did not observe that type of deformations in simulated canals instrumented with NiTi S5. Łaszkiewicz et al. more often observed elbow or zipp deformations in canals prepared with hand K-flex files (64.7%) than in case of NiTi Profile instruments (13.3%) [21]. Wilkoński et al. studying S-shaped canals preparation with Mtwo (single length and crown-down), ProTaper, WaveOne and Reciproc [17] observed a single case of aberration elbow or ledge type in case of WaveO” and Mtwo (single-length technique). Instrumentation with ProTaper caused those types of aberrations in 3 out of 10 cases. No aberrations were observed in canals prepared with Reciproc and Mtwo (crown-down technique). Yang et al. in 4 endo-blocks with “L-shaped” canals (out of 10) instrumented with ProTaper and 2 prepared with Hero 642 observed deformations of ledge or elbow type [18]. Kroprowicz et al. observed: 3 case (out of 10) of ledge or elbow creation while preparing canals with WaveOne and 2 if instrumented with ProTaper or Reciproc [25].

Different methods allow assessing the canals’ curve are described in the literature. The most popular and most frequently used one was presented in 1971 by Schneider [27]. Later Pruet et al. observed that two root canals with the same angle can have a different curvature
radius and updated the method providing the value of the radius made it possible to define
the curvature of the canal [28]. Their invention is of great clinical importance because the
bigger the canal curve and the lower the curvature radius; the risk of straightening the
channel is higher. The curvature parameters influence on the instrument’s overload and
subsequently positively correlates with the risk of instrument separation. In 2005 the term
CAA was introduced by Günday et al. as well as two new parameters describing the
anatomical part of the curved canals: initial distance of curvature and curvature length [29,30].

Bürklein et al. conducted research on 80 patent canals with diameter in apex ≥15
ISO and curvature angle 25–39°, using Reciproc, WaveOne, Mtwo, as well as ProTaper
instruments, T and observed a similar degree of natural curvature preservation in all
instruments—no statistically significant difference between them [31]. Results acquired in
our research differ from those presented by other authors. It may be due to the different
technique of curvature angle measurement. Because the canal was prepared on the working
length shortened for 0.5 mm, the simulated canals’ apical foramen was not prepared and
subsequently its location was not changed. Each instrument removed material from both
inner and outer canals’ curvature. As a result, the A-line was moved inside and crossing
that line with the outer canals curvature was altered. That crossing was located in a bigger
distance concerning canal orifice and more outer to the primary location. As a result,
the curvature angle increased. Comparison of examined groups proved a statistically
significant difference only for canals prepared with WaveOne and Mtwo (taper 7% and
6%). Mtwo and ProTaper Next has the same taper (6%) of the last instrument used in
the study. However, while comparing WO group (taper 7%) and PN group (taper 6%)
no statistically significant difference was observed. Similar results were observed when
comparing PN and MT groups. On the basics of the obtained data, it cannot be clearly
stated if the statistically significant difference was caused by the usage of instruments with
different taper or by differences in alloys used for the manufacturing of the particular type
of instruments.

The increase of simulated canals volume after mechanical preparation was observed
in each examined group. Li et al. investigating the changes in the volume of 5 single-
rooted premolars prepared with hand ProTaper instruments till size F3 [32] by means of
microcomputed tomography, observed the decrease in canals volume in each case. The
decrease in volume was correlated with the type of canal according to Wein classification,
and it was estimated between 4.8% and 150.2%. Sillelioglu et al. assessed the changes of
canals volume in 50 molar teeth using a microcomputed tomography [33]. They divided
the material into two groups. In group I, canals were prepared with the step-back technique
and hand K-files made out of NiTi alloy. In the second group, ProTaper instruments and
the crown-down technique were used. They determined volume changes in group I: 56.2% to
71.9% and in II: 72.8–78.2%. Wei et al. examined the changes in simulated canals volume
prepared withProTaper Universal vs Reciproc and K3XF, utilizing the MicroCT method.
The least change in volume in each part was observed in canals instrumented with K3XF
and the highest in ones instrumented with Reciproc [34].

The volumetric changes should be correlated to different tapers of used instruments.
WaveOne instruments are characterized by the biggest taper (7%) out of used instruments,
that is why the volume change was the biggest. Mtwo and PtoTaper Next have the same
taper, so the volume changes in MT and PO groups did not have a statistically significant
difference. The hand K-files with the smallest taper caused the lowest volume changes in
K group.

In most of the papers regarding the rotary NiTi instruments, the apex transportation
and preservation of the canals’ natural shape were analyzed [7,8,24]. Barankiewicz and
Pawlicka in the research on Race instruments used for the preparation of L-shaped canals
observed apex transportation outside [24]. Radwariski et al. reported apex transportation
in each instrument used (WaveOne Gold, ProTaper Next, ProTaper Universal) [7]. The aver-
age values of transportation for WaveOne Gold vs. ProTaper Next were negative—inside
transportation. The results obtained for Pro Taper Universal elucidated that the transporta-
tion was more pronounced than in ProTaper Next and WaveOne Gold. Authors proved that the differences in transportation between those pairs of instruments were statistically significant ($p < 0.05$). No statistically significant difference in transportation was obtained in groups where canals were instrumented with NiTi instruments. Statistically significant differences were observed while comparing the K group with each group’s rotary system. Observed changes may be caused by the different taper of the last instrument used.

The presented results show possibility to use MR Imaging (called in literature as MR Microscopy) for visualization of the root canals topography [14]. The quality of the MR visualization does not depend on complication in shape of the canals. An important aspect of the MRI measurements is to obtain high contrast between the cavities and the tooth. This may be achieved by filling cavities with water or water solution of paramagnetic ions having high MR signal [13]. Another important aspect is maximal space resolution possible to achieve in reasonable time. In the used sequence (3D SE) increasing twice the 3D resolution requires four time longer experimental time (assuming that lower S/N does not require additional signal accumulation), while the necessary disk space increases 8 times [15]. For artificial teeth the time of the measurements is not the most critical problem. However, to implement this technique in vivo, it is necessary to decrease it substantially. Using the solution with the appropriate T1 and T2 values for filling cavities may decrease the total measurement time. However, more promising solution might be used for the fast acquisition techniques. Sequences based on the train of the echoes instead of the single echo are especially favorable. Another possibility—sequences based on the gradient echo, seems to be less useful because of their sensitivity to the magnetic susceptibility artefacts. Magnetic resonance microscopy/imaging is not yet used in clinical dental practice. It was not until the STRAFI technique that proton imaging of real hard dental tissues was possible, although the resolution of such registered images left much to be desired, and it was not possible to distinguish individual types of hard tissues. Therefore, a valuable and reasonable solution for imaging tooth structure seems to be the use of SPI and spin echo methods, which are available or possible to implement on standard equipment and allow imaging of both mineralized parts and dental pulp [15]. The SPI method was used in previous studies for caries detection in vitro [13]. Once the current difficulties in magnetic resonance imaging are overcome, it will be possible to introduce this type of visualization technique to the level of in vivo analysis. In the future, magnetic resonance microscopy may become a diagnostic tool supporting the work of a clinician. The results obtained indicate the possibility of using the spin-echo based magnetic resonance imaging technique for spatial mapping of external tooth topography and the course and structure of tooth root canals for therapeutic, diagnostic, and didactic purposes [35,36]. Determination of parameters through the use of magnetic resonance imaging techniques may improve the planning and conduct of endodontic treatment in the future [37,38].

5. Conclusions

The obtained results indicate that each of the examined systems enables a safe preparation of curved canals. While, the differences between the particular files are so in significant, it is impossible to select a specific one, especially recommended for L-shaped canals preparation.

The application of the spin echo based magnetic resonance imaging technique for visualization of the internal topography of the “artificial” root’s canals appears to be a valuable method for in vitro research concerning volumetric alterations following mechanical root canals preparation.

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22. Jardine, A.P.; Rosa, R.A.; Santini, M.F.; Zaccara, I.M.; Só, M.V.; Kopper, P.M. Shaping ability of rotatory or reciprocating instruments in curved canals: A micro-computed tomographic study. Braz. Oral Res. 2016, 30, e86. [CrossRef] [PubMed]

23. Radwański, M.; Łęski, M. Porównanie stopnia opracowania sztucznych kanałów w kształcie litey „L” dwoma systemami maszynowymi: eS5 EndoStar i PrTaper. e-Dentico 2014, 3, 98–107.

24. Barankiewicz, D.; Pawlicka, H. Opracowanie kanałów korzeniowych narzędziami rotacyjnymi RaCe- badania laboratoryjne. J. Stomatol. 2011, 64, 314–327.

25. Koprowicz, A.; Łęski, M.; Pawlicka, H. Properties of mechanical endodontic instruments and the quality of the simulated canal preparation. Dent. Med. Probl. 2016, 53, 476–482. [CrossRef]

26. Kroczyńska, P.; Gaj, E.; Dura, W.; Lipski, M. Ocena deformacji naturalnego przebiegu kanału korzeniowego w następstwie preparacji z użyciem ręcznych narzędzi stalowych i systemu rotacyjnych narzędzi niklowo-titanowych S5. Mag. Stomatol. 2013, 9, 182–186.

27. Schneider, S.W. A comparison of canal preparations in straight and curved root canals. Oral Surg. Oral Med. Oral Pathol. 1971, 32, 271–275. [CrossRef]

28. Pruett, J.P.; Clement, D.J.; Carnes, D.L. Cyclic fatigue testing of nickel-titanium endodontic instruments. J. Endod. 1997, 23, 77–85. [CrossRef]

29. Günday, M.; Sazak, H.; Garip, Y. A comparative study of three different root canal curvature measurement techniques and measuring the canal access angle in curved canals. J. Endod. 2005, 31, 796–798. [CrossRef]

30. Schäfer, E.; Diez, C.; Hoppe, W.; Tepel, J. Roentgenographic investigation of frequency and degree of canal curvatures in human permanent teeth. J. Endod. 2002, 28, 211–216. [CrossRef]

31. Bürklein, S.; Hinschitz, K.; Dammaschke, T.; Schäfer, E. Shaping ability and cleaning effectiveness of two single-file systems in severely curved root canals of extracted teeth: Reciproc and WaveOne versus Mtwo and ProTaper. Int. Endod. J. 2012, 45, 449–461. [CrossRef] [PubMed]

32. Li, K.Z.; Gao, Y.; Zhang, R.; Hu, T.; Guo, B. The effect of a manual instrumentation technique on five types of premolar root canal geometry assessed by microcomputed tomography and three-dimensional reconstruction. BMC Med. Imaging 2011, 11, 14. [CrossRef] [PubMed]

33. Sillelioglu, H.; Ölmek, A.; Atabek, D. Micro-computed tomography evaluation of root canal preparation using rotary system and hand instrument in young permanent molars. J. Pediatr. Dent. 2015, 3, 61–66.

34. Wei, Z.; Cui, Z.; Yan, P.; Jiang, H. A comparison of the shaping ability of three nickel-titanium rotary instruments: A micro-computed tomography study via a contrast radiopaque technique in vitro. BMC Oral Health 2017, 17, 39. [CrossRef]

35. Tanasiewicz, M. Magnetic resonance imaging in human teeth internal space visualization for requirements of dental prosthetics. J. Clin. Exp. Dent. 2010, 2, 6–11. [CrossRef]

36. Tanasiewicz, M.; Weglarz, W.; Gruwel, M.L.H.; Trzcionka, A. Lokalizacja ubytków próchnicowych z wykorzystaniem obrazowania magnetyczno-rezonansowego. Mag. Stomatol. 2008, 13, 32–37.

37. Tanasiewicz, M. Magnetic resonance imaging in endodontic treatment prediction. J. Med. Imaging Radiat. Sci. 2010, 41, 127–132. [CrossRef]

38. Weglarz, W.P.; Tanasiewicz, M.; Kupka, T.; Skórka, T.; Sulek, Z.; Jasinski, A. 3D MR Microscopy of dental cavities. An in vitro study. Solid State NMR 2004, 25, 84–87. [CrossRef]