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The Cyclic Fatigue Resistance of Different Lengths of CM Gold Wire and CM Blue Wire NiTi Alloy Endodontic Rotary Files: An In Vitro Study

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Abstract: Background: The objective of the present study was to measure and compare how the length of CM Gold Wire and CM Blue Wire NiTi alloy endodontic rotary files impacts their resistance to cyclic fatigue. Methods: A total of 40 sterile endodontic rotary files were chosen and allocated to the following study groups: (A) 25.06 CM Gold wire NiTi alloy endodontic rotary files, 31 mm in length (n = 10); (B) 25.06 CM Gold wire NiTi alloy endodontic rotary files, 25 mm in length (n = 10); (C) 25.06 CM Gold wire NiTi alloy endodontic rotary files, 21 mm in length (n = 10); and (D) 25.06 CM Blue wire NiTi alloy endodontic rotary files, 17 mm in length (n = 10). A specialized device was designed using artificial root canal systems made from stainless steel for the dynamic cyclic fatigue tests, with an apical diameter of 250 µm, curvature angle of 60°, radius of curvature of 5 mm, lengths of 31, 25, 21, and 17 mm, and a 6% taper. An individual operator determined failure of the endodontic rotary instrument through direct observation and the tests were filmed so as to precisely measure the exact time to failure. The results were analyzed using ANOVA and Weibull statistical analysis. Results: The results found statistically significant differences across all study groups ($p < 0.05$). Conclusions: Rotary file length is inversely proportional to the cyclic fatigue resistance of the 25.06 CM Gold wire NiTi alloy at 31 mm, 25 mm, and 21 mm in length and of the 25.06 CM Blue wire NiTi alloy 17 mm length endodontic rotary files, with a greater length contributing to lower resistance to cyclic fatigue.

Keywords: CM Blue wire; CM Gold wire; cyclic fatigue; endodontics; length; NiTi alloy

1. Introduction

The nickel–titanium (NiTi) alloys used for manufacturing endodontic rotary files are roughly 56% nickel and 44% titanium by weight [1]. This alloy has unique characteristics including shape memory and super-elasticity when compared with traditional stainless-steel endodontic instruments [2]; this can have positive impacts on root canal treatments by improving the accuracy, speed, and safety of treatment [3]. Additionally, manufacturers continuously enhance the geometric design of NiTi alloy endodontic rotary files, which has been proven to impact their mechanical behavior. That being said, failure during root canal shaping remains a concern [4] as it makes it more difficult to disinfect the entire root canal system and negatively impacts root canal treatment prognosis as a result [5].

Several factors influence the chance of failure of NiTi alloy endodontic rotary files, including whether or not the instruments have a cross-section design [6]. Other factors include the apical diameter and taper [7], pitch, flute length, and helix angle [8]. Additional factors that can affect the risk of fracture include dynamic characteristics of these instruments such as canal geometry [5] and torque [9], in addition to which process is used for their manufacture, i.e., electropolishing, heat treatment, or ion implantation [9]. Furthermore, NiTi alloy endodontic rotary files are often used alongside sodium hypochlorite, which may be corrosive to the NiTi alloy, reducing its resistance to failure [10]. Physical mechanisms of failure include cyclic fatigue, torsional fatigue, or a combination thereof [11]. Torsional failure is caused by the tip of an NiTi alloy endodontic rotary file becoming trapped in one of the root canal walls while the instrument keeps rotating, causing the file to fracture once it exceeds the elastic limit of the metal [12–14]. Flexural bending fatigue is a result of the rotary file being repeatedly exposed to traction and compression cycles at the point of maximum curvature of the root canal; the plastic eventually deforms as a result of these stresses, sometimes to the point that the file unexpectedly fractures [11,15,16]. When a file is in the process of breaking, the high density of surface defects exacerbates the crack nucleation stage, and cracks continue to propagate during each loading cycle until the same load as before becomes too great for the remaining intact material, resulting in failure [17].

As a result, manufacturers have sought to reduce failure rates on NiTi alloys and improve the geometrical design of NiTi alloy endodontic rotary files. A study by Pruett et al. found that increased apical diameter reduced the cyclic fatigue resistance of NiTi alloy endodontic rotary files, analyzing teeth with curvature angles of 30°, 45°, and 60° and a curvature radius of 2 and 5 mm [18]. Furthermore, Gambarini et al., reported that increased taper measurements also resulted in the files having lower resistance to cyclic fatigue, using a testing machine at a 45° bend [19]. Kwak et al., found that the helix angle and pitch also reduced the cyclic fatigue resistance of NiTi alloy endodontic rotary files, observed in a stainless-steel artificial canal with a curvature radius of 3 mm and curvature angle of 90° [8]. That being said, the impact of length of NiTi alloy endodontic rotary files on their cyclic fatigue resistance has yet to be studied, despite there being a wide range of lengths available to clinicians, suited to carrying out interventions in all types of root canal systems [20]. The alteration of the axis, a non-active component of the instrument, is what results in the difference in lengths. This variation in total length of the instruments can impact the distribution of stress during the instrumentation process [20]. Researchers have observed that the overall difference in length can lead to different changes to the mechanical properties of NiTi files [20].

This study was carried out to measure and compare how the length of CM Gold wire and CM Blue wire NiTi alloy endodontic rotary files impacts their cyclic fatigue resistance, with a null hypothesis (H_0) stating that the length does not impact the resistance to dynamic cyclic fatigue of CM Gold wire and CM Blue wire NiTi alloy endodontic rotary files.

2. Materials and Methods

2.1. Study Design

A total of 40 sterile, unused CM Gold wire and CM Blue wire NiTi alloy endodontic rotary files were selected for use in this in vitro study. A controlled experimental trial was carried out at the Department of Stomatology of the Faculty of Medicine and Dentistry at the University of Valencia (Valencia, Spain), between September and October 2022. The selected CM Gold wire and CM Blue wire NiTi alloy endodontic rotary files were randomly distributed into the following study groups: (A) 25.06 controlled-memory (CM) Gold wire NiTi alloy endodontic rotary files, 31 mm in length (Ref.: IRE 3102506, D, Endogal, Galician Endodontics Company, Lugo, Spain) ($n = 10$); (B) 25.06 CM Gold wire NiTi alloy endodontic rotary files, 25 mm in length (Ref.: IRE 2502506) ($n = 10$); (C) 25.06 CM Gold wire NiTi alloy endodontic rotary files, 21 mm in length (Ref.: IRE 2102506) ($n = 10$); and (D) 25.06 CM Blue wire NiTi alloy endodontic rotary files, 17 mm in length (Ref.: SIRKE, EK2, Endogal Kids) ($n = 10$).

2.2. Scanning Electron Microscopy Analysis

All NiTi endodontic rotary files were first assessed via scanning electron microscopy (SEM) (HITACHI S-4800, Fukuoka, Japan) at 30×, 300×, and 600× magnification. This prior assessment was conducted by the Central Support Service for Experimental Research of the University of Valencia (Burjassot, Spain) using the following exposure parameters: 20.0 kV acceleration voltage, a resolution between −1.0 nm at 15 kV and 2.0 nm at 1 kV, and magnification from 100× to 6500×. These parameters were used to carry out surface characterization so as to rule out any further manufacturing surface defects and evaluate and compare the geometric design of the NiTi endodontic rotary files (Figure 1). This methodological procedure has been used in previous studies [6,21,22].

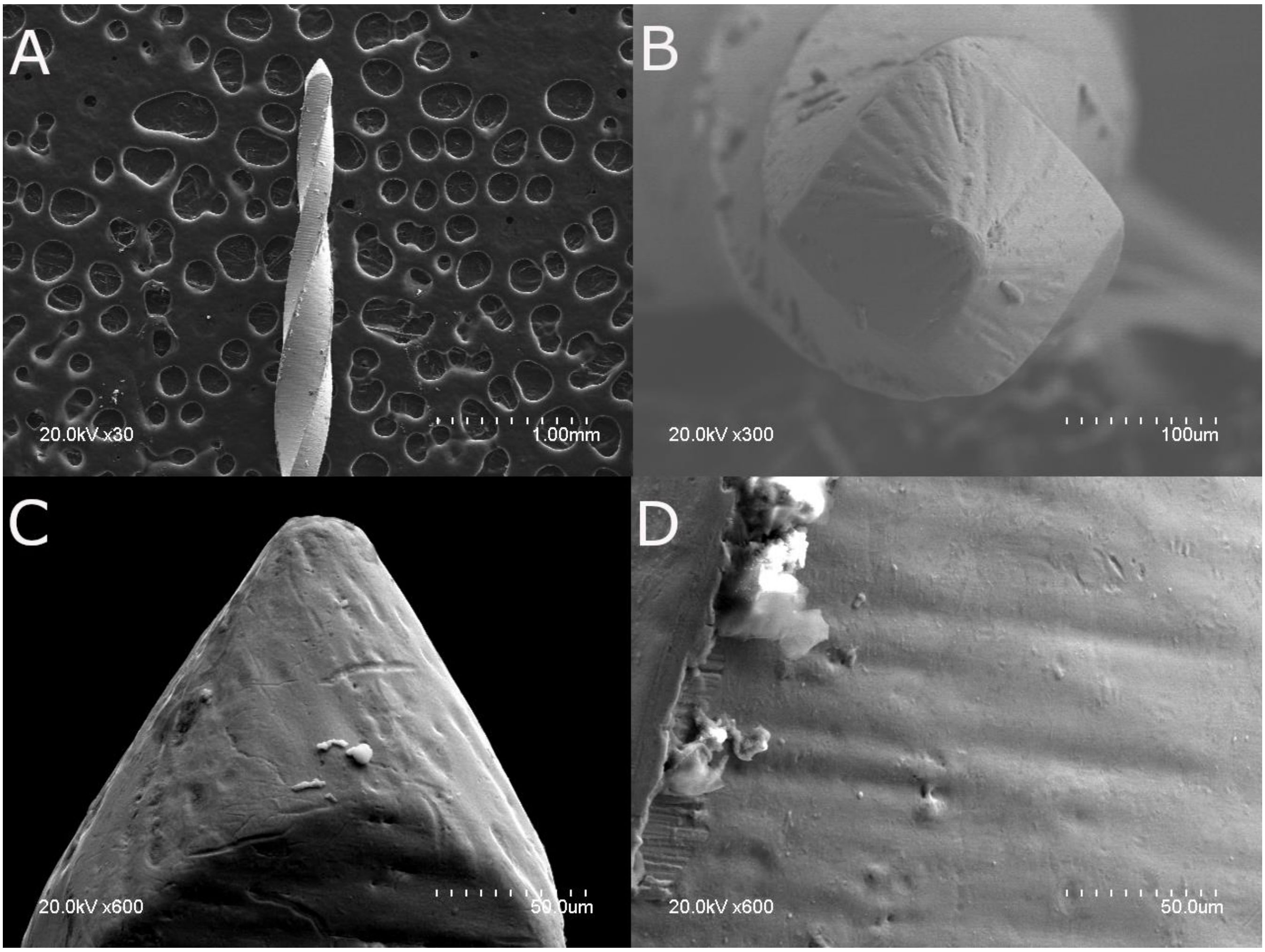

Figure 1. NiTi alloy endodontic rotary file SEM analysis at (**A**) 30×, (**B**) 300×, and (**C**,**D**) 600× magnification.

2.3. Energy-Dispersive X-ray Spectroscopy Analysis

In addition, all NiTi endodontic rotary files under study at the Central Support Service for Experimental Research of the University of Valencia (Burjassot, Spain) underwent an energy-dispersive X-ray spectroscopy (EDX) using the following exposure parameters: magnification from 100× to 6500×, acceleration voltage of 20 kV, and a resolution between −1.0 nm at 15 kV and 2.0 nm at 1 kV in order to evaluate the makeup of the chemical components of the files used in the static fatigue tests. This was determined using atomic weight percent measurement, taken at three randomized locations (Figure 2). This methodological procedure has also been used in previous studies [6,21,22].

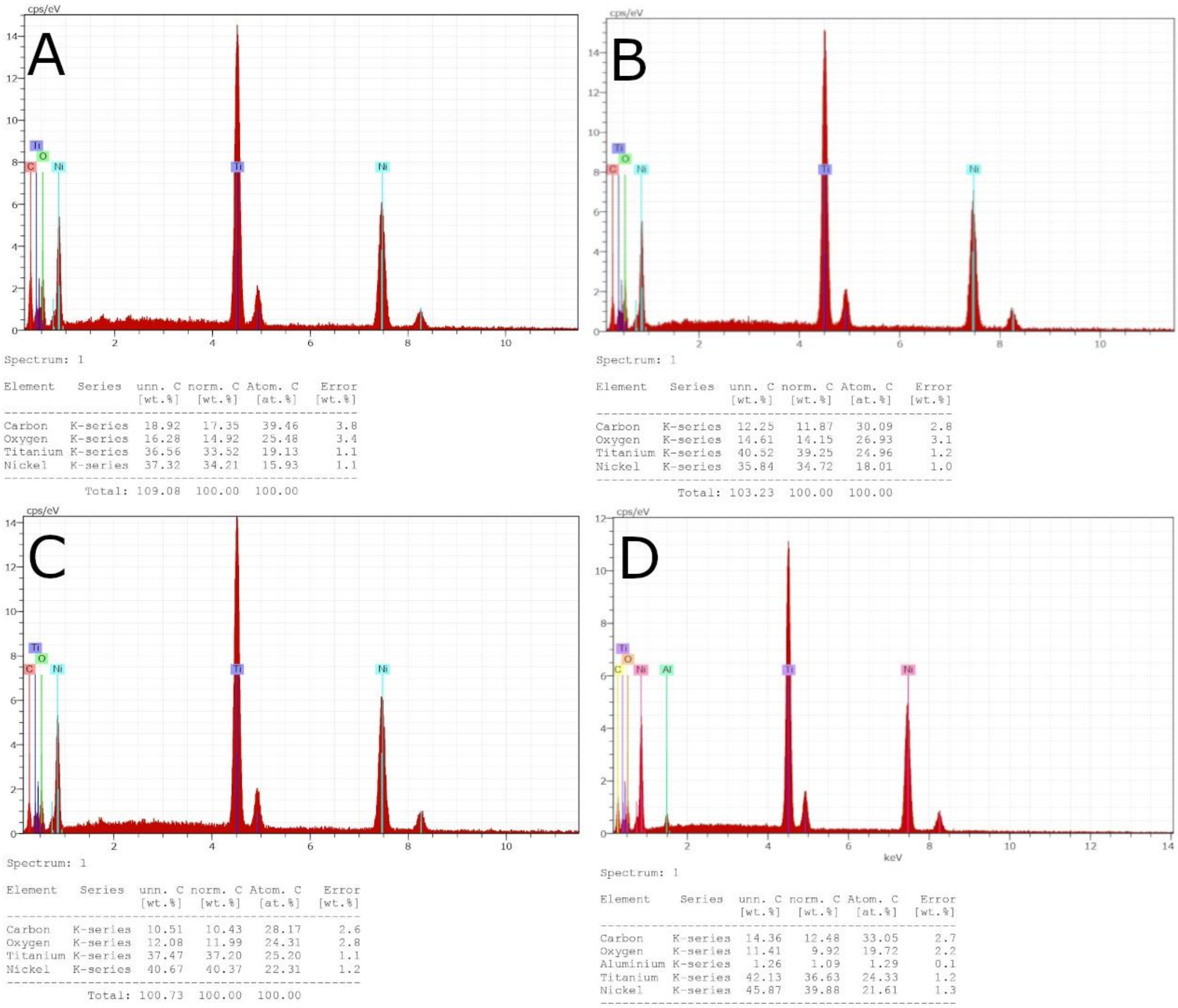

Figure 2. (**A**) EDX micro-analysis of the 25.06 CM Gold wire NiTi alloy endodontic rotary files, 31 mm in length; (**B**) 25.06 CM Gold wire NiTi alloy endodontic rotary files, 25 mm in length; (**C**) 25.06 CM Gold wire NiTi alloy endodontic rotary files, 21 mm in length; and (**D**) 25.06 CM Blue wire NiTi alloy endodontic rotary files, 17 mm in length.

2.4. Experimental Cyclic Fatigue Model

Dynamic cyclic fatigue tests were conducted using the aforementioned customized device (Utility Model Patent No. ES1219520) [23] at room temperature (20 °C) to analyze the mechanical behavior of the instruments as per Martins et al. [24]. The structure of the fatigue-testing device was designed via computer-aided design and engineering (CAD/CAE) and 2D/3D software (Midas FX+®, Brunleys, Milton Keynes, UK), and it was printed with a 3D printer (ProJet® 6000 3D Systems©, Rock Hill, SC, USA) (Figure 3).

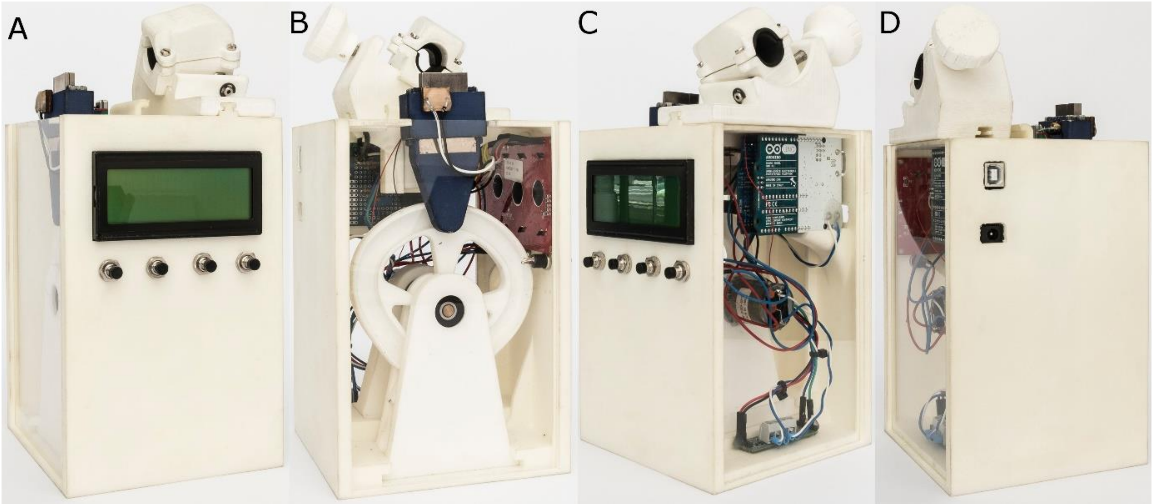

Figure 3. (**A**) Front, (**B**) back, (**C**) right, and (**D**) left surfaces of the dynamic cyclic fatigue device.

The custom artificial root canals were performed using CAD/CAE 2D/3D software v1 for inverse engineering technology as per Schneider's measuring technique [21], with a 60° curvature and 5 mm radius of curvature. In addition, four lengths were configured to match the different lengths of the NiTi alloy endodontic rotary file from each study group: 31 mm, 25 mm, 21 mm, and 17 mm. Electrical discharge machining (EDM) molybdenum wire-cut technology (Cocchiola S.A., Buenos Aires, Argentina) was used to create the artificial root canal from stainless steel. This process ensures that the root canal walls and the NiTi endodontic reciprocating files are in close contact. The artificial root canal was positioned on its support, and a light-dependent resistor (LDR) sensor (Ref.: C000025, Arduino LLC®, Ivrea, Italy), located at the apex of the artificial canal, was used to when the endodontic rotary instrument failed. The LDR sensor quantified the continuous light source emitted by a high-brightness white LED (20,000 mcd) (Ref.: 12.675/5/b/c/20k, Batuled, Coslada, Spain), which was placed opposite the artificial root canal. An LDR (Ref.: C000025, Arduino LLC®) sensor with a frequency of 50 ms was used to detect the light signals that were emitted by this LED sensor so as to determine the exact time of failure.

The speed and direction of the movement generated by the brushed DC gear motor (Ref.: 1589, Pololu® Corporation, Las Vegas, NV, USA) and controlled by the driver (Ref.: DRV8835, Pololu® Corporation, Las Vegas, NV, USA) were transferred via a roller bearing system (Ref.: MR104ZZ, FAG, Schaeffler Herzogenaurach, Germany). A lineal guide (Ref.: HGH35C 10249-1 001 MA, HIWIN Technologies Corp. Taichung, Taiwan) was used to aid in moving the artificial root canal support in an entirely axial motion. All the NiTi endodontic rotary files were used in conjunction with a torque-controlled motor and 6:1 reduction handpiece (X-Smart Plus, Dentsply Maillefer, Baillagues, Switzerland). All of the files were utilized at 300 rpm and 2.3 N/cm torque, as per the manufacturer's instructions.

All of the NiTi endodontic files were subjected to a total of 60 pecking movements per minute within the dynamic cyclic fatigue device, in concordance with the parameters of a previous study [23]. In order to reduce friction between the rotating files and the artificial canal walls, researchers applied a specialized high-flow synthetic oil (Singer All-Purpose Oil; Singer Corp., Barcelona, Spain), designed to lubricate mechanical parts.

All NiTi endodontic rotary files were used until the point of fracture. The time to failure was observed and recorded.

2.5. Statistical Tests

The selected CM Gold wire and CM Blue wire NiTi alloy endodontic rotary files were divided into study groups, in keeping with the proportions determined by the researcher, and with a power of 80%. Additionally, when testing the null hypothesis H_0, an effect size of 0.606 could be observed. The mean values of the four groups were equal by means of a one-factor ANOVA test for independent samples, factoring in a significance level of 5%. Statistical analysis was carried out using SAS 9.4 (SAS Institute Inc., Cary, NC, USA). Standard deviation (SD) and mean values were used for quantitative data for the descriptive analysis. Comparative statistics were calculated by comparing the time to failure in seconds using the ANOVA test. Researchers also conducted a Weibull statistical analysis. The results were considered significant at $p < 0.05$.

3. Results

Table 1 shows the mean and SD values for the time to failure for each of the study groups, expressed in seconds.

Table 1. Descriptive analysis of time to failure (seconds).

Study Group	n	Mean	SD	Minimum	Maximum
31 mm	10	358.33 [a]	38.21	302.50	412.60
25 mm	10	420.78 [b]	5.83	413.00	431.10
21 mm	10	485.12 [c]	43.43	399.10	538.10
17 mm	10	577.39 [d]	40.26	502.70	632.60

[a, b, c, d] Statistically significant differences between groups ($p < 0.05$).

The ANOVA detected statistically significant differences in time to failure for all of the study groups ($p < 0.0001$); between the 31 mm and 25 mm length study group ($p = 0.0019$), between the 31 mm and 21 mm length study groups ($p < 0.0001$), between the 31 mm and 17 mm length study groups ($p < 0.0001$), between the 25 mm and 21 mm length study groups ($p = 0.0014$), between the 25 mm and 17 mm length study groups ($p < 0.0001$), and between the 21 mm and 17 mm length study groups ($p < 0.0001$).

The scale distribution parameter (η) of Weibull statistics revealed statistically significant differences in time to failure between all of the study groups ($p < 0.001$) (Table 2). In addition, the shape distribution parameter (β) also detected statistically significant differences in time to failure between the 31 mm and 25 mm length study groups ($p < 0.0001$), between the 25 mm and 21 mm length study groups ($p < 0.0001$), and between the 25 mm and 17 mm length study groups ($p < 0.0001$). However, no statistically significant differences in time to failure were revealed between the 31 mm and 21 mm length study groups ($p = 0.3403$), between the 31 mm and 17 mm length study groups ($p = 0.1510$), or between the 21 mm and 17 mm length study groups ($p = 0.6500$) (Table 2).

Table 2. Weibull statistics of the time to failure for each study group.

Study Group	Weibull Shape (β)				Weibull Scale (η)			
	Estimate	St Error	Lower	Upper	Estimate	St Error	Lower	Upper
31 mm	11.2531	2.8108	6.8970	18.3606	374.8087	11.1397	353.5990	397.2905
25 mm	76.9101	18.0821	48.5131	121.9290	423.5920	1.8497	419.9820	427.2329
21 mm	15.8995	4.1752	9.5030	26.6016	502.6726	10.4693	482.5664	523.6165
17 mm	18.7645	4.7630	11.4097	30.8603	594.4943	10.5473	574.1773	615.5303

4. Discussion

The results of this study reject the null hypothesis (H_0) that the length of CM Gold wire and CM Blue wire NiTi alloy endodontic rotary files has no effect on their dynamic cyclic fatigue resistance.

The results derived from the present study indicated that the rotary file length negatively impacts the resistance to fracture of NiTi alloy endodontic rotary files. It is, therefore, recommended that clinicians properly select the instrument length in relation to the root canal system length, paying closer attention to those cases that require long NiTi alloy endodontic rotary files as there is more surface in contact and stress and, therefore, the concentration of cumulative stress is greater. The fracture mechanisms of NiTi alloy endodontic rotary files are of clinical interest because instrument failure can jeopardize good clinical outcomes of root canal treatment [25].

The rates of failure of the NiTi alloy endodontic rotary files can be influenced by a combination of different variables that converge during the root canal shaping procedure. Therefore, while challenging, isolating each variable individually is essential to assess their respective influence on cyclical fatigue. Experimental studies provide a controlled environment in which a clinical setting is reproduced, enabling unique or a reduced number of variables to be analyzed. In addition, further clinical studies are needed to replicate clinical conditions and extrapolate the cyclic fatigue results to a clinical setting. However, it is difficult to homogenize the radius, curvature angle, apical diameter, hardness, and cross-section of the root canals, which can bias the study by introducing additional variables [26]. As a result, custom-made dynamic cyclic fatigue devices can be used to individually analyze the influence of the specific variable under study. Regrettably, there are normative regulations for the characteristics of the custom-made cyclic fatigue devices, nor is there an international standard for testing the behavior of NiTi endodontic rotary instruments with a taper greater than 2% in response to cyclic fatigue [27]. We selected CM Gold wire and CM Blue wire NiTi alloy endodontic rotary files with 6% taper, according to previous studies [21–23]; moreover, all CM Gold wire and CM Blue wire NiTi alloy endodontic rotary files presented the same taper to avoid including another variable. In addition, a 60° curvature angle was selected for the custom artificial root canals, according to previous studies [21–23].

Previous studies highlighted the effect mechanical and performance qualities of NiTi alloy endodontic rotary files have on their cyclic fatigue resistance [28]. Additionally, the geometric design of files directly affects the total mass of the instrument, which has proven to be statistically significant in determining the stiffness and, therefore, the resistance to the cyclic fatigue of the files. The length of the files increases the mass of the instruments and may also explain the impact of this particular variable on cyclic fatigue resistance. Versluis et al. experimentally found that the number of threads directly correlates with increased flexural stiffness [29]; meanwhile, Al Raeesi et al. reported that a shorter pitch design is correlated with increased cyclic fatigue resistance of glide path instruments [30]. Additionally, Rui et al., experimentally showed that a greater helix angle value has a positive effect on the mechanical behavior of the instrument under conditions of bending and torsion [31]. Pruett et al., studied the cyclic fatigue of NiTi alloy endodontic rotary files and discovered that instruments with shafts of larger diameter failed in fewer cycles than files with lower diameters under identical testing conditions [18].

Additionally, comparisons of the 31 mm length, 25 mm length, and 21 mm length 25.06 CM Gold wire NiTi alloy endodontic rotary files and the 17 mm length CM Blue wire rotary files also showed that CM Blue wire NiTi alloy endodontic rotary files had higher static cyclic fatigue resistance than CM Gold wire NiTi alloy endodontic rotary files. That being said, it is challenging to isolate the most determinant or relevant variable or variable combination when it comes to the resistance to cyclic fatigue of NiTi endodontic rotary files. These results are corroborated when comparing the cyclic fatigue resistance of the NiTi CM Blue wire alloy from the Reciproc Blue endodontic reciprocating system with the NiTi CM Gold wire alloy from the Wave One Gold endodontic reciprocating system. The Reciproc Blue endodontic reciprocating system had a higher cyclic fatigue resistance than the Wave One Gold endodontic reciprocating system, perhaps owing to its cross-sectional design [32,33].

The Weibull analysis enables estimation of the probability of a material presenting fracture over time. A more vertical curve denotes greater predictability of the mechanical behavior of a material, since it would indicate that all samples fracture at the same moment. However, a more horizontal curve denotes greater unpredictability of the behavior of a material as it could fracture at any time. These are expressed with shape and scale parameters. A larger scale, a broader distribution, and a shape parameter greater than 1 indicate that the failure rate increases with time. Regrettably, the limitations of the present study prevented an analysis of additional lengths to standardize the NiTi alloy, pitch, helix angle, apical diameter, speed, taper, and manufacturing process. Furthermore, difficulties in standardizing samples meant that the study was not carried out in a clinical environment.

5. Conclusions

Rotary file length is inversely proportional to the cyclic fatigue resistance of the 25.06 CM Gold wire NiTi alloy, 31 mm, 25 mm, and 21 mm in length, as well as of the 25.06 CM Blue wire NiTi alloy 17 mm in length, whereby a greater length contributes to a lower resistance to cyclic fatigue.

Author Contributions: All study authors contributed to the research, supervision, writing, review, and editing of the present study. Conceptualization, V.F.-L. and B.S.-M.; data curation, I.F.-M., V.F.-M. and B.M.B.; visualization, Á.Z.-M., C.R.-S. and S.P.G. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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