An Investigation of Cyclic Fatigue Resistance Between Reciproc® Blue and RC-Pro Blue in Reciprocating Motion: A Comparative Study

Abstract

Research Question

Is there a difference in cyclic fatigue resistance between two files, Reciproc® Blue and RC-Pro blue, in vitro?

Background

Reciproc® blue files became available in 2016 and have demonstrated superior cyclic fatigue resistance. More recently, other manufacturers, primarily from China, have produced cheaper files claiming they are identical to Reciproc® blue in all respects. Studies conducted in Brazil compared Reciproc® files with replica files and found them to have similar cyclic fatigue resistance to the original. However, there have been no comparative studies between Reciproc® blue and RC-Pro blue.

Methods

Six Reciproc® blue and six RC-Pro blue files, both with a tip diameter of 0.25mm, were randomly acquired for comparison. Both were purchased from online suppliers. Both groups were run to failure using the manufacturer's setting for Reciproc®. An apparatus was constructed to mimic a curved canal of 60°. The experiment was conducted at room temperature.

Data Collection and Analysis

Raw data was recorded in minutes and seconds and subsequently converted to seconds. A significance level of 95% was set. Statistical analysis was performed using SPSS™ software. An independent samples T-Test was conducted to compare the means of the time to fracture between the two file groups.

Findings

A statistically significant finding demonstrated that RC-Pro blue had a longer time to fracture than Reciproc® blue.

Conclusion

Replica files may perform as well as or better than their original counterparts in terms of cyclic fatigue resistance despite being cheaper.

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Introduction

Root canal treatment is a critical procedure utilised by dentists to remove bacterial infections from within the root canal system to help and save a compromised tooth. The success of this treatment relies on the effective chemo-mechanical disinfection of the root canal system with the use of files to mechanically shape the canals, and irrigant's to help disinfect the intricate canal network (Dennis et al., 2021; Raducka et al., 2023).

Dentists initially relied on stainless steel instruments for the mechanical shaping of the canal, and whilst effective, there was a high risk of procedural errors due to the instruments' limited flexibility (Chu & Lockwood, 2015; Shim et al., 2017).

The introduction of nickel-titanium (Ni-Ti) rotary files resulted in a fundamental shift in endodontics. Due to the superior mechanical properties of Ni-Ti, which will be discussed in-depth below, the root canal treatment process was greatly simplified and more predictable (Zanza et al., 2022).

Despite these advancements, the risk of instrument fracture remains, especially in more challenging anatomy such as curved canals and sclerosed canals (Pillay et al., 2020). In response to these risks, manufacturers have developed novel techniques and innovative thermo-mechanical treatments to control and enhance the properties of the Ni-Ti files (Algar et al., 2022; K et al., 2023). One such thermomechanical treatment is found in the Reciproc® blue file (Reciproc blue), which has enhanced the flexibility and increased its resistance to cyclic fatigue, which will be explained in greater detail below (Adigüzel & Turgay, 2017). However, as the market has evolved lower cost 'replica files' have emerged, marketed as having identical characteristics to their brand name counterparts (Martins et al., 2021). However, a significant gap exists in the literature, with a lack of data comparing the performance, durability and manufacturing consistency of these replica files against the original well researched systems which they imitate (Tarragó, 2025).

In this study, we aim to compare the cyclic fatigue resistance of Reciproc Blue with its 'replica', RC-Pro blue. This direct comparison will determine if there is a significant difference in their resistance to cyclic fatigue.

Background

Mechanical Instrumentation

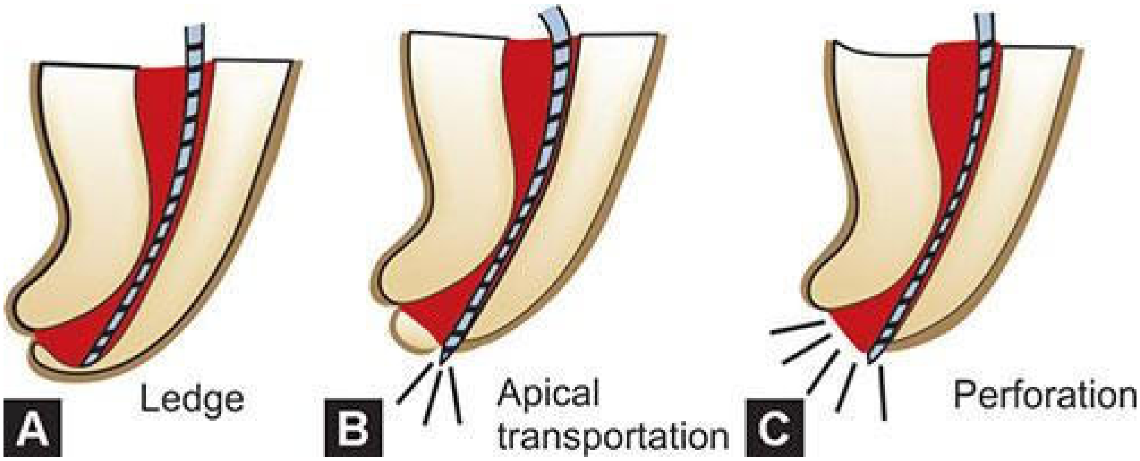
Root canal infections occur when micro-organisms colonise the root canal system. These micro-organisms, predominantly bacteria, along with their by-products, infiltrate the root canal system and subsequently access the peri-radicular tissues (Marian-Vladimir, 2020). This triggers an inflammatory response within the periapical region, leading to pathological changes in the surrounding tissues (Wong et al., 2021).

Root canal treatment is a fundamental procedure designed to save teeth compromised by this bacterial infection. The treatment aims to eliminate bacteria within the root canal system and prevent future reinfection (European Society of Endodontology, 2006; Gulabivala & Ng, 2014). The process of disinfection is accomplished through chemo-mechanical disinfection, an essential component of root canal treatment (Metzger et al., 2010). It involves using endodontic files to shape the canal, which in turn facilitates the irrigant to contact as much of the root canal system as possible for chemical disinfection (Nagendrababu et al., 2020). The treated root canal space is then obturated, where the space is filled and sealed, to prevent reinfection, allowing the body to heal (Chaniotis & Ordinola-Zapata, 2022).

Traditionally, stainless-steel hand files have been used for the mechanical preparation of the root canal system during endodontic treatment. This approach, whilst effective in experienced hands, presents several notable challenges in clinical practice. The process is time-consuming, particularly in complex canal anatomies, and demands considerable operator skill and experience to achieve predictable results (De Deus et al., 2021). The limited flexibility of stainless-steel hand files, especially in larger file sizes, contributes to procedural complications when negotiating curved canals (Baruwa et al., 2024). These complications may cause iatrogenic errors, including canal transportation, ledge formation and, in severe cases, perforation of the root structure, all of which can compromise treatment outcomes (Lambrianidis, 2006). **Figure 1** below shows a pictorial representation of these iatrogenic errors.

Figure 1

A pictorial representation of; A: ledge, B: apical transportation, C: perforation (Garg & Garg, 2014)



The advent of Ni-Ti rotary instrumentation has fundamentally transformed contemporary endodontic practice. These instruments possess superior elasticity (the ability to bend and return to shape) and flexibility (the ability to bend without breaking) compared to stainless-steel hand files, properties that derive from the unique crystallographic structure of the nickel-titanium alloy (Agrawal et al., 2024; Liang & Yue, 2022). The mechanical cleaning and shaping process has become more efficient, reducing chairside time whilst enhancing predictability. The properties of Ni-Ti have reduced the technique sensitivity associated with root canal preparation, allowing operators of differing experience and skill levels to achieve more consistent results (Zanza et al., 2021). These technological advancements have enabled practitioners to more closely adhere to Schilder's (1974) principles of canal preparation, which emphasise maintaining the original canal path, preserving the apical constriction, and creating a continuously tapering preparation whilst respecting the inherent anatomical complexities of the root canal system (Schilder, 1974).

Despite these advancements in Ni-Ti instruments, there is still a risk of iatrogenic errors, especially in more complex canal anatomy. The introduction of Ni-Ti endodontic files has greatly reduced the incidence of blockages, ledges, perforations and transportation, although there is also the perception that they fracture more easily than stainless steel hand files (Peters & Peters, 2010). A Canadian study comparing the incidence of instrument related mishaps within a hospital setting found a 40%

decrease when Ni-Ti rotary instruments were used as opposed to stainless steel hand instruments. However, the author of this study pointed out that regardless of the instruments being used, the incidence of iatrogenic errors increased with the complexity of the tooth, such as the more canals present and the degree of curvature of these canals (Matoug-Elwerfelli et al., 2022). This ultimately led to an increase in ledge formation and instrument separation (Chaniotis & Ordinola-Zapata, 2022).

Ni-Ti files

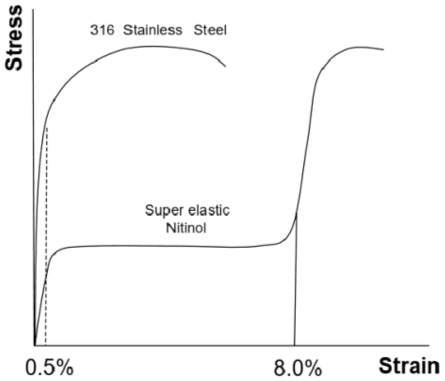
Ni-Ti was first discovered in 1959 at the Naval Ordnance Laboratory, where it was initially developed for military applications (Akira, 2008). Researchers identified that this novel alloy, then called Nitinol, exhibited remarkable shape memory properties, allowing it to return to its original shape following deformation (Walia et al., 1988). This near equi-atomic alloy has since proven to be biologically compatible for dental applications.

Ni-Ti possesses exceptional super-elastic characteristics, enabling it to recover its original shape without plastic deformation until reaching 7% to 8% strain—nearly 40 times greater than that of stainless steel (Walia et al., 1988).

Figure 2 below shows a graphical representation of the stress and strain properties of both stainless steel and Ni-Ti. These unique metallurgical properties make Ni-Ti particularly advantageous for endodontic instruments, as they can better negotiate curved canals whilst maintaining their structural integrity.

Figure 2

The stress strain comparison between Stainless steel and N-Ti (Bajpai et al., 2020).



The introduction of Ni-Ti into endodontics has significantly transformed mechanical instrumentation by providing files with superior flexibility and resistance to cyclic fatigue compared to traditional stainless-steel instruments (Peters, 2004). This enhanced flexibility allows clinicians to prepare canals with complex anatomies more predictably whilst reducing the risk of iatrogenic errors such as canal transportation, ledging and perforations (Haapasalo & Shen, 2013).

Ni-Ti was first introduced to dentistry in the late 1980s, with Walia et al. (1988) pioneering its use for endodontic files. The unique properties of Ni-Ti provided distinct advantages over traditional stainless-steel instruments (Parashos & Messer, 2006; Thompson, 2000). These properties, discussed above, allowed for the maintenance of the original canal anatomy, especially in curved canals, whilst reducing the risk of iatrogenic errors such as transportation, zipping and ledge formation (Peters, 2004). Furthermore, these instruments could be used with rotary handpieces, which reduced the time required for canal preparation and simplified the treatment process (Haapasalo & Shen, 2013).

The first generation of Ni-Ti rotary files, introduced in the early 1990s, featured a passive cutting tip and fixed tapers (Gutmann & Gao, 2012). These instruments, characterised by systems such as ProFile (Dentsply Maillefer) were designed with a non-cutting tip (McSpadden, 2007). Whilst these instruments demonstrated superior canal-centring ability compared to stainless steel files, they were limited by their reduced cutting efficiency and the need for multiple instruments to achieve the desired canal shape (Bergmans et al., 2001). The second generation emerged in the late 1990s with active cutting edges and varying tapers, exemplified by ProTaper (Dentsply Maillefer) and K3 (SybronEndo) systems (Parashos & Messer, 2006). These files featured multiple tapers within a single instrument and more aggressive cutting edges, which improved efficiency but introduced concerns about increased screw-in forces and potential for file separation (Yared, 2008). The manufacturing process of these early generations involved grinding the Ni-Ti wire, which could introduce surface defects that potentially served as stress concentration points, ultimately increasing susceptibility to fatigue failure (Cheung & Darvell, 2007).

The third generation of Ni-Ti files marked a significant advancement through thermal treatment processes applied to the Ni-Ti alloy (Shen et al., 2013). This innovation, introduced in the mid-2000s, significantly altered the crystalline structure of the alloy, resulting in increased flexibility and resistance to cyclic fatigue (Gutmann

& Gao, 2012). Systems such as M-Wire (Dentsply Tulsa Dental), used in WaveOne and ProTaper Next, and R-phase (SybronEndo), utilised in Twisted Files, demonstrated up to 400% greater resistance to cyclic fatigue compared to conventional Ni-Ti instruments (Larsen et al., 2009). The improved fatigue resistance allowed for safer instrumentation of curved canals and reduced the risk of intracanal separation (Shen et al., 2013). The fourth generation, emerging around 2010, further refined the thermomechanical processing of Ni-Ti alloys, implementing different thermal treatments such as controlled memory wire technology (CM-Wire) and blue heat treatment (Zupanc et al., 2018). These files, characterised by HyFlex CM (Coltene-Whaledent) and Reciproc blue (VDW), demonstrated remarkable flexibility, allowing the instruments to bend significantly without returning to their original shape until heated, thus reducing the restoring force applied to canal walls during instrumentation (Shen et al., 2013). This generation exhibited exceptional fatigue resistance and allowed for the development of novel motion kinematics, including reciprocation (Bürklein et al., 2019).

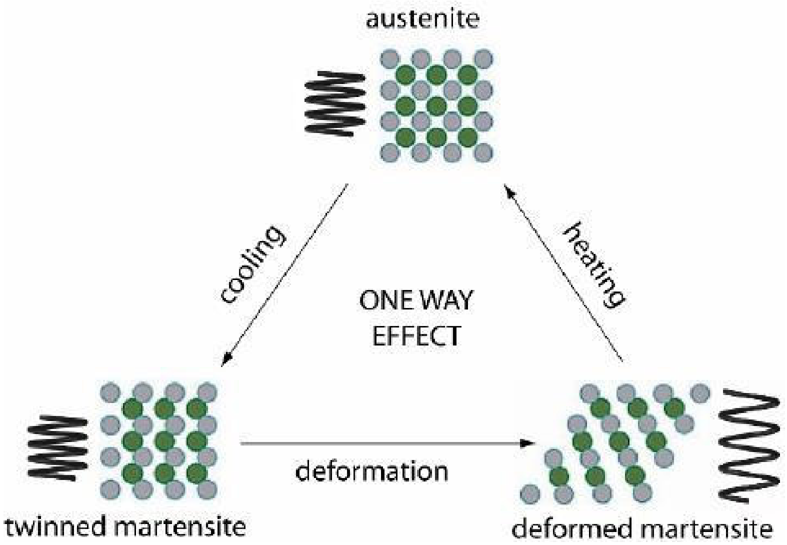
The fifth generation of Ni-Ti files, developed in the mid-2010s, incorporated advanced metallurgy with unique manufacturing processes to optimise performance (Zupanc et al., 2018). Files such as ProTaper Gold (Dentsply Sirona) and EdgeFile (EdgeEndo) utilised proprietary thermal treatments that altered the transformation temperatures of the alloy, resulting in instruments with different mechanical properties at room temperature versus body temperature (Hieawy et al., 2015). The most significant innovation of this generation was the electrical discharge machining (EDM) process, used in the manufacture of HyFlex EDM files (Coltene-Whaledent). Unlike traditional grinding methods, EDM uses spark erosion to shape the Ni-Ti wire, resulting in a file with a hardened surface that significantly improves cutting efficiency and wear resistance (Pirani et al., 2016). Recent developments have focused on reducing the number of files required for complete canal preparation, with many contemporary systems advocating a single-file technique (Bürklein et al., 2019). This approach, utilised in systems such as WaveOne Gold (Dentsply Sirona) and Reciproc blue (VDW), simplifies the instrumentation protocol and reduces the time required for canal preparation (Keskin et al., 2017).

Super elasticity and control memory of Ni-Ti

Ni-Ti possesses the significant properties of super elasticity and shape memory which is derived from the crystallographic structure of this alloy (Thompson, 2000). Ni-Ti exists in two temperature dependant crystalline phases: austenite, which is stable at higher temperatures, and martensite, which is stable at lower temperatures (Otsuka & Ren, 2005). The super elasticity is due to stress induced transformation above the alloy's austenitic finish temperature. When stress is applied, the crystalline structure transforms, allowing the alloy to accommodate the strain far better than stainless steel, as seen above (Otsuka & Ren, 2005). This can be seen in Figure 3. Once the stress is removed, the Ni-Ti alloy can spontaneously revert to its austenitic phase from its martensitic phase. This is especially useful in endodontics as it allows the file to navigate curved canals whilst minimising lateral forces on the walls, thereby preserving the original canal anatomy (Shen et al., 2013). Conventional Ni-Ti, whilst still flexible, can still experience considerable restoring forces when within a curved canal; this can lead to canal transportation or file separation, especially in severely curved canals (Haapasalo & Shen, 2013).

Figure 3

The schematic sketch shows the martensite-austenite phase transition for the one-way shape memory effect on macroscopic level (spring) and atomic level (green- and gray-colored balls) as well known for Ni-Ti (Bormann et al., 2010)



Controlled memory wire (CM wire) refers to Ni-Ti alloy that has undergone specific thermomechanical processing, resulting in an alloy with a predominantly martensitic crystal structure at both room and body temperature (Testarelli et al., 2011). Within CM wire, this martensitic structure manifests in two distinct forms: a twinned martensitic phase and a detwinned martensitic phase. In the twinned phase, the crystalline structure arranges itself into a self-accommodating lattice, whilst in the detwinned phase, the crystalline structure reorientates in response to applied stress. This unique metallurgical characteristic enables the wire to maintain a pre-bent shape without immediately returning to its original form. Furthermore, the martensitic transformation significantly enhances flexibility, permitting the endodontic instruments to navigate severe canal curvatures without exhibiting the immediate shape memory effect typically observed in conventional austenitic Ni-Ti instruments (Zupanc et al., 2018).

Further innovations, such as heat-treating alloys resulting in M-wire, R-phase, Gold wire and blue wire, each employing a specific process to refine the balance between flexibility and cutting efficiency (Zupanc et al., 2018). These processes can increase the cyclic fatigue resistance, more on this below, and allow the alloy to stay in the martensitic phase at lower temperatures, therefore conferring enhanced flexibility and fatigue resistance during clinical use (Shen et al., 2011).

Manufacture of files

The manufacturing of Ni-Ti files in endodontics also plays a crucial role in determining their mechanical properties and, consequently, their clinical performance. These properties can influence the file’s ability to withstand different stresses, alter its flexibility and resist fatigue. Various manufacturing processes have been developed to produce Ni-Ti files, and each imparts distinct characteristics to the files produced.

One of the first and most conventional methods for producing files is the grinding process. This involved the mechanical grinding of a Ni-Ti blank to create the desired cross section, cutting edge and taper. Although widely used, this process can have some limitations. The grinding process can create micro-fractures and surface defects that can then act as stress concentration points, potentially leading to file separation (Goo et al., 2017).

The process of twisting is also another manufacturing process whereby the Ni-Ti wire is twisted after it has undergone a thermal treatment. This process can potentially preserve the integrity of the Ni-Ti wire. It can preserve the integrity of the original crystalline structure, reduce surface defects and cracks, increase its flexibility and enhance cyclic fatigue resistance (Miyai et al., 2006).

Electrical discharge machining is also a novel manufacturing process used to produce endodontic files. This process involved the erosion of the Ni-Ti material from the wire using electrical discharge between an electrode and the wire. This process creates a characteristic surface on the wire with micro-craters and a hardened recast layer. This recast layer can aid in enhanced cutting efficiency whilst simultaneously reducing surface defects (Pedullà et al., 2015).

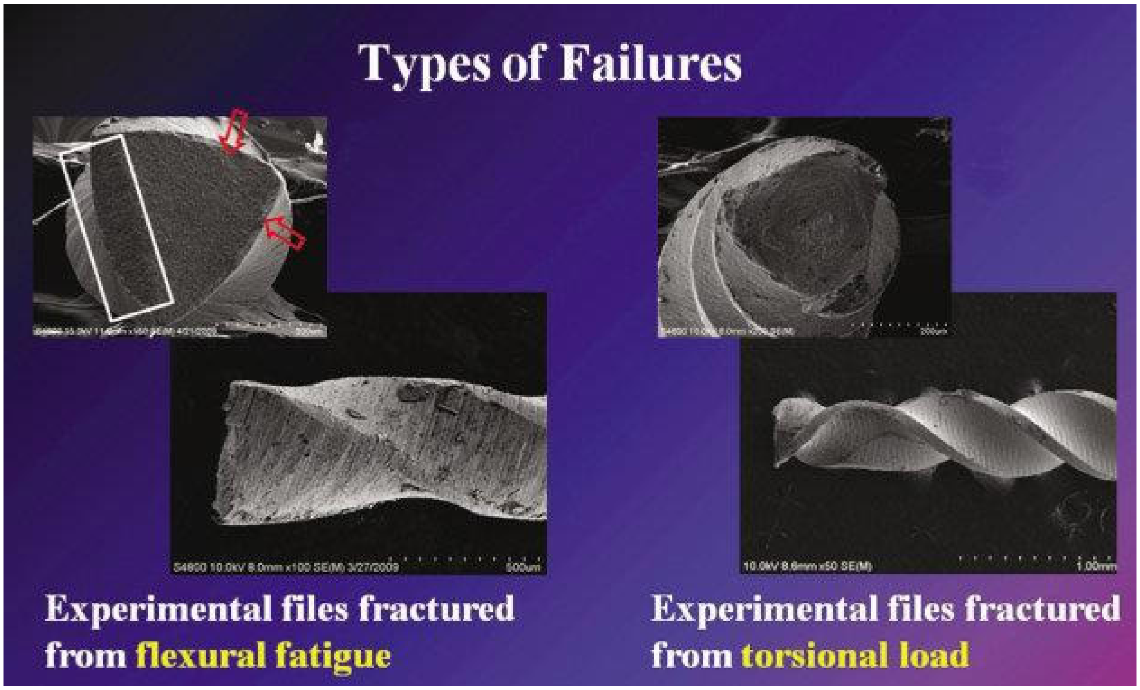
Fatigue of files

When files break inside a canal, it's due to either cyclic fatigue or torsional fatigue. Torsional fatigue occurs when a portion of the instrument becomes locked within the canal whilst the shank continues to rotate. Fracture of the instrument's tip happens when the torque applied by the handpiece exceeds the metal's elastic limit. This is more likely to occur in narrow, calcified canals where the file tip can easily bind against the canal walls (De Pedro-Muñoz et al., 2024; Plotino et al., 2009).

Cyclic fatigue, conversely, happens when an instrument rotates freely within a curved canal. This creates alternating tension and compression cycles at the point of maximum flexure. As the file rotates in a fixed position, the outer half of the file (facing the outside of the curve) experiences tension, whilst the inner half undergoes compression. The repeated cycling between tension and compression leads to microscopic crack formation and propagation within the metal's crystalline structure (Plotino et al., 2009). Over time, these micro-cracks coalesce and grow, ultimately resulting in the complete separation of the instrument. This type of failure is particularly common in canals with acute curvatures, where the stress concentration at the point of maximum flexure is significantly higher. This will be further explained below. The types of failure can be seen in Figure 4.

Figure 4

Fracture modes of Nickel-Titanium rotary files. (a, b) Experimental files fractured from flexural fatigue (H.-C. Kim, 2011).



Types of Failures

Experimental files fractured from flexural fatigue

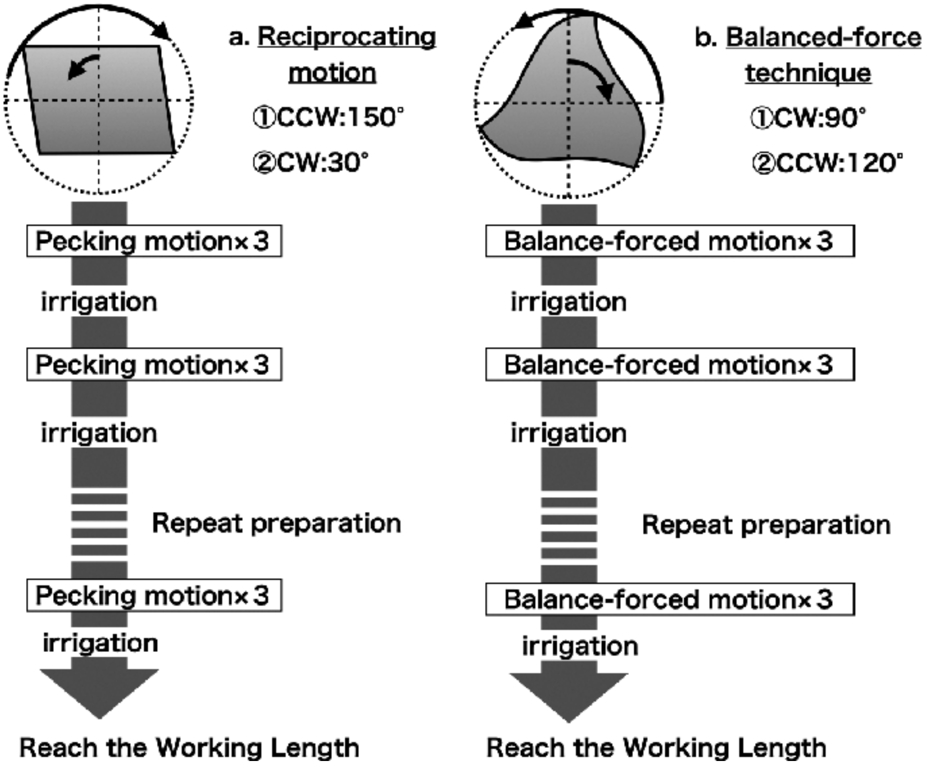
Experimental files fractured from torsional load

The balanced force technique was introduced by Roane et al. (1985) to help maintain the original canal anatomy whilst reducing iatrogenic errors, particularly when preparing curved or sclerosed canals. This technique involves introducing a hand file within the canal until resistance is met. The clinician then rotates the file clockwise by 90 degrees to engage the dentine, followed by a larger counterclockwise motion of

270 degrees with slight apical pressure. This controlled movement effectively cuts and removes dentine whilst distributing stress evenly along the file (Lambrianidis, 2006; Roane et al., 1985). The protocol for this is outlined in Figure 5.

Figure 5

Reciprocating motion and glide path protocols (Masashi Yamada et al., 2023)



This methodical approach significantly reduces the risk of instrument separation and canal transportation. It also helps to preserve the natural canal morphology, which is fundamental to successful endodontic treatment. The balanced force technique represents an important advancement in hand instrumentation, allowing clinicians to better adhere to Schilder's principles of canal preparation, which emphasises respecting and conforming to the original canal anatomy when mechanically preparing (Gulabivala & Ng, 2014; Hargreaves & Cohen, 2010; Peters, 2004).

Current adaptations

The balanced force technique has been further pioneered and adapted for Ni-Ti engine-driven files with the advent of reciprocating motion. This innovation utilises engine-driven files with a reciprocating rotation like that of the balanced force technique originally developed for hand instrumentation (Yared & Ramli, 2013). The development of this motion effectively allows the file to engage the cutting surface and disengage multiple times, thus reducing the amount of cyclic fatigue the file experiences during canal preparation (Zanza et al., 2021).

Specific file systems such as WaveOne ® and Reciproc ® were specifically designed with this motion in mind. These systems were manufactured to exploit the advantages of reciprocating motion, which effectively redistributes stress within the file during canal preparation. This mechanical innovation has greatly reduced treatment time whilst simultaneously increasing predictability and effectiveness (Schäfer & Florek, 2003; Yared, 2010). The reciprocating motion also helps dissipate the stress within the file, reducing the risk of file fracture due to cyclic fatigue. As the file undergoes motion in both the forward and reverse directions, this motion leads to less tension on the instruments, which increases its cyclic fatigue resistance (De Pedro-Muñoz et al., 2024). This enables dentists to adhere more closely to the principles of respecting and preserving original canal anatomy during mechanical preparation (Metzger et al., 2010).

Reciproc blue files

Reciproc blue files represent a culmination of various processes and techniques to create a versatile file system that helps navigate different root canals. These files are produced using the grinding process with several notable proprietary modifications to enhance their performance (Martins, Silva, Marques, Belladonna, Simões-Carvalho, Vieira, et al., 2021). The files start as M-Wire, a Ni-Ti wire having undergone thermomechanical treatment (Ozlek & Gunduz, 2021). Once the file is ground, it undergoes a heat treatment which creates a visible layer of titanium oxide on the surface of the file, giving it its characteristic blue colour (De-Deus et al., 2017). This post grinding heat treatment is thought to reduce surface imperfections and microcracks, which noted above is a drawback of the grinding process. The blue heat treatment also enhances the flexibility of the file, improves cyclic fatigue resistance and stabilises the crystalline structure of the file (De-Deus et al., 2017; Generali et al., 2020; Hou et al., 2021). This will be further explained below.

Figure 6

A Reciproc blue file (VDW, 2024)

A notable feature of the Reciproc blue file is the unique S-shaped cross-sectional geometry. This cross-section minimises the number of contact points between the file and the canal, lowering friction and allowing more aggressive dentine removal (Martins, Silva, Marques, Belladonna, Simões-Carvalho, Vieira, et al., 2021). The minimisation of the surface area in contact with the dentine can also increase torsional resistance. This reduces the risk of file separation due to torsional fatigue, as the file is less likely to bind to the dentine within the canal (De-Deus et al., 2017). The larger flutes, due to this cross-section, can also allow for improved debris removal, preventing blockages (Doğanay Yıldız & Arslan, 2019). It is also theorised that the cross-sectional shape reduces the central metal core or bulk of the file, aiding in increased flexibility and reducing stiffness (Ríos-Osorio et al., 2024).

Literature Review

A search of current literature was undertaken using online databases. This would help the researcher to understand the current literature, identify any previous studies that have been completed and to find a gap in the research.

Two online databases were used for the literature search. The search was restricted to the period from 2015 to current and was conducted in English. This approach restricted the scope of the research but ensured that the findings remained current and practically relevant for clinical practice.

Two databases were used in the conduct of this literature review:

1. Wiley online library (mainly but not exclusively limited to the International endodontic journal and Australian endodontic journal)
2. ScienceDirect (mainly but not exclusively limited to Journal of endodontics and Journal of dental science)

Endodontic Journals, material science and metallurgy journals, especially those pertaining to Ni-Ti and associated material were used. A further restriction was added as only articles subscribed to by SimplyEndo, under the University of Chester could be accessed. This further refined the number of articles which could be accessed.

There were multiple searches that were undertaken with key words used to help refine the searches to be more relevant. The Boolean operator ‘AND’ was also used to help refine searches.

The search terms followed by the number of articles found is compiled in Table 1 below.

Table 1

Key search words and results before and after refinement. (author's own table).

Search terms	Number of results	Relevant articles (after refinement)
Reciproc blue and cyclic fatigue	217	176
RC-Pro blue and cyclic fatigue	22	0
Reciproc blue replica files	22	1
Reciproc blue and counterfeit files	6	2

A total of 176 relevant articles were found in both databases for Reciproc blue and cyclic fatigue. However, there were no relevant articles found for RC-Pro blue and cyclic fatigue. The search was then expanded to include other file systems which may have alternative names, with the terms 'replica' and 'counterfeit' used to help identify them. These searches resulted in three articles which were used in this literature review. However, there were no articles found for RC-Pro blue and cyclic fatigue. The search was then expanded to include other file systems which may have alternative names, with the terms 'replica' and 'counterfeit' used to help identify them.

The use of Ni-Ti rotary files for mechanical debridement of the root canal system has increased significantly in the field of endodontics. This is due to the inherent properties of the Ni-Ti alloy, particularly its superelasticity and shape memory effect. These properties provide the instruments with remarkable flexibility, which is a substantial improvement over traditional stainless-steel files (Grande et al., 2023; Tabassum et al., 2019).

The flexibility of Ni-Ti files allows for the creation of more centred and continuously tapered canal preparations. This allows for effective irrigation and obturation of the root canal system (Grande et al., 2023). Additionally, improvements in thermomechanical processing have led to the development of Ni-Ti alloys. These include M-wire and heat-treated variants, which exhibit improved cyclic fatigue resistance compared to conventional Ni-Ti files (Kwak et al., 2021). This improvement results in a lower incidence of file separation.

The design and material properties of modern Ni-Ti rotary files have enabled clinicians to manage more complex and challenging root canal anatomies with greater confidence (Abdellatif et al., 2024). The flexibility of these instruments allows them to negotiate curved and narrow canals with minimal transportation of the original canal path (Hage et al., 2020). This helps to preserve the natural anatomy of the root canal system (Pruett et al., 1997). Furthermore, the enhanced cutting efficiency of these files is attributed to their unique cross-sectional designs and flute patterns. This facilitates the effective removal of dentine and debris, whilst reducing operator fatigue and treatment time (Zupanc et al., 2018).

Wire Manufacture and Heat Treat

Contemporary Ni-Ti rotary files are made of an equi-atomic alloy of Nickel (around 54-56%) and Titanium (around 44-46%) by weight. Different manufacturers may introduce minute variations to the ratio of both metals within the alloy to influence the properties of the subsequent alloy (Oh et al., 2023).

The Ni-Ti is used for its distinct properties: super elasticity and its shape memory effect, as discussed above. These properties are attributed to the crystalline structure of Ni-Ti, specifically the austenitic and martensitic phases.

Contemporary endodontic files all start as blanks, conditioned billets or rods of Ni-Ti, which are then subjected to different manufacturing processes. These Ni-Ti blanks are subjected to specialised thermomechanical processes to produce different performances.

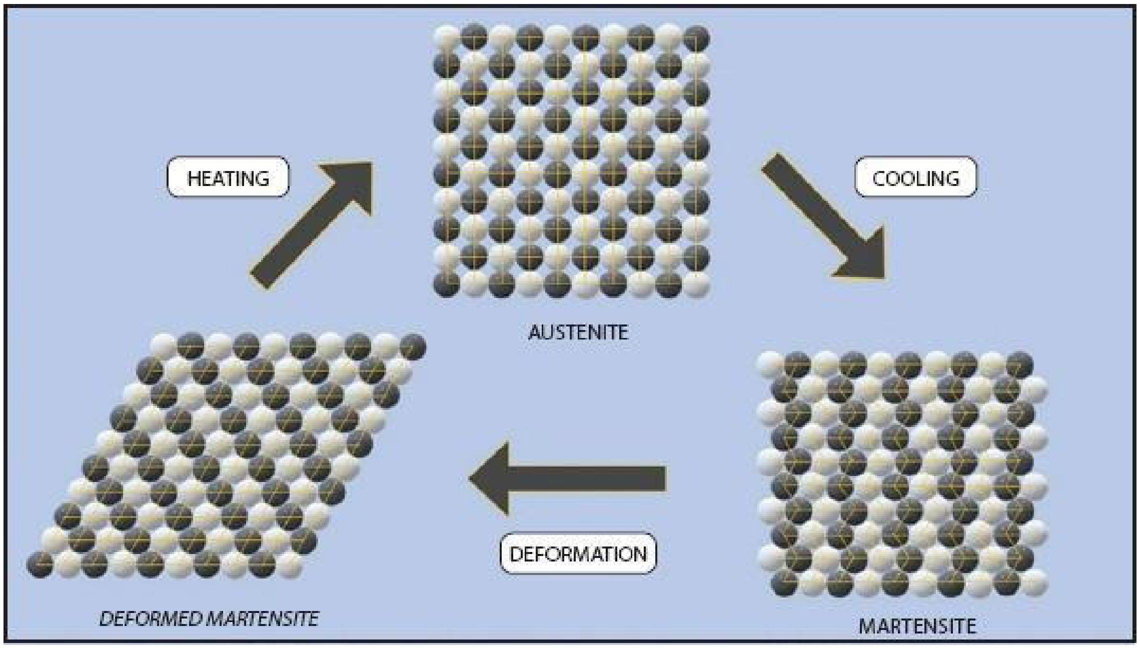
Controlled memory wire, developed in 2010, is a Ni-Ti alloy with a lower nickel content (approximately 52%) (Tabassum et al., 2019). This allows the wire to be highly flexible and means the wire does not exhibit super-elasticity. This means the wire will not spring back to its original shape once deformed and will retain its new shape at room and body temperatures (Oh et al., 2023). The controlled memory wire also exhibits exceptional flexibility when compared to files made of conventional Ni-Ti and its other variants at room temperature. Hyflex CM files are made using this process. However, one drawback is that the maximum torque that controlled memory wire can withstand is lower than conventional Ni-Ti (Pereira et al., 2015).

R-phase wire is another form of Ni-Ti used for endodontic files. The R-phase characteristic pertains to the crystallographic structure of the Ni-Ti within the wire

(Krishnan et al., 2019). The crystals can form in an intermediate phase between austenite and martensite. These crystals exhibit a rhombohedral crystallographic structure, which gives the wire improved torsional and cyclic fatigue resistance, as well as giving it a lower elastic modulus, allowing for greater flexibility (Santos et al., 2016). See *Figure 7* for a pictorial representation of the R-phase crystallographic structure.

Figure 7

The R-phase crystallographic structure. (Tabassum et al., 2019)



The 'blue' heat treatment used in Reciproc blue is when M-wire blanks are subjected to a post machining heat treatment (Pereira et al., 2015). This differentiates these files from traditional mechanical processing used to create M-wire itself. The process of creating the blue heat treat is proprietary, and the exact temperatures, duration and atmospheric pressure are not publicly known (Tabassum et al., 2019).

The blue colour of this heat treatment results from a layer of titanium oxide forming on the surface of the wire. It is reported to be around 100nm thick with a uniform distribution across the file (Generali et al., 2020; Pereira et al., 2015). This layer appears to demonstrate good wear resistance as no obvious wear can be found on the surface after use (De-Deus et al., 2017). However, microcracks could be present underneath this layer, but this is an area which warrants further research as no evidence could be found for this (Generali et al., 2020). The Titanium oxide layer is theorised to give the file good corrosion resistance, which can be beneficial as the file will be subjected to a harsh chemical environment within the root canal system during use, as this can reduce the amount of Nickel released (Pohl et al., 2008).

The ‘blue’ heat treat not only affects the surface finish of the wire but also changes the crystalline microstructure of the M-wire alloy itself (Generali et al., 2020). One of the key ways this is done is by creating a much finer crystalline grain structure, which has smaller grain sizes as compared to the original Reciproc® file (Campos et al., 2024). This enhances both the strength and the fatigue resistance of this alloy (Campos et al., 2024).

There is also a notable difference in the phase composition of the blue heat-treated alloy, with an increase in the levels of martensite as well as the presence of R-phase at room temperature (Gündoğar et al., 2019; Silva et al., 2023). The new composition can increase the flexibility of the file at room temperature (Seracchiani et al., 2022). The level of the martensitic phase within this alloy can also allow it to be pre-bent, with an ability to retain some of that curve and remain deformed (Keskin et al., 2017). This permits easier access to hard-to-reach canals and can help files bypass curves within a canal (Altufayli et al., 2022).

One of the drawbacks of this heat-treatment is the reduction in the hardness of the alloy when compared to M-wire (De-Deus et al., 2017; Zupanc et al., 2018). This, in theory, can reduce the cutting efficiency of the file due to reduced wear resistance, but this is offset by the s-shaped cross section, which is very efficient in cutting (Uygun, 2020; VDW, 2024).

Transformation Temperatures:

The mechanical properties that enable the clinical performance of Reciproc blue files is due to the inherent thermomechanical processing of the NI-Ti alloy (Gündoğar & Özyürek, 2017; Oh et al., 2020). Understanding the mechanical foundation is imperative to interpret the performance of this file system. Key to this concept is the understanding of the reversible, thermoelastic solid state phase transformations of the two primary crystal structures within the alloy: martensite and austenite (Almeida et al., 2019; Özyürek et al., 2018).

Austenite is the high temperature phase characterised by a body centred cubic crystal structure. This crystal phase is relatively strong, hard and stiff with an elastic modulus of 80-90 Giga Pascals (GPa), which relates to 0.8 to 0.9 Newtons per cm² (N/cm²) (Braga et al., 2021; K et al., 2023). One of the important qualities of the austenite crystal is its superelasticity, which allows it to undergo significant deformation under stress and recover its original shape upon stress removal. This is due to its stress induced transformation into the martensite crystal phase (Krishnan et al., 2019). Conventional non-heat-treated Ni-Ti files have transformative temperatures below that of ambient conditions, which means that they exist purely in the austenitic phase during clinical use.

Martensite, on the other hand, is the low temperature phase which comprises a monoclinic crystal structure. In contrast to austenite, martensite is significantly softer, more ductile, and more flexible, with an elastic modulus of 30-40 GPa, which corresponds to 0.3 to 0.4 N/cm² (Braga et al., 2021; K et al., 2023). One of the defining qualities of this phase is its ability to recover from deformations. This shape memory effect where a deformation which occurs in the martensitic phase can be fully recovered by heating the alloy back into its austenitic phase. This phase also exhibits a substantially higher cyclic fatigue resistance, one of the primary causes of instrument separation (Özyürek et al., 2018; Shim et al., 2017).

The phase transformation between austenite and martensite is not always a direct process. Under specific conditions, often obtained through the thermomechanical process, there is an intermediate stage where R-phase can form (Almeida et al., 2019; Uygun, 2020). The R-phase is a type of martensitic transformation that precedes and competes with the formation of martensitic crystals (Kwak et al., 2021). The R-phase exhibits a very low elastic modulus, with an overlap with the martensitic phase (Shim et al., 2017).

The transition between the different phases occurs over a range of temperatures. These temperature points are critical in dictating the alloy's phase composition at any given temperature and its mechanical properties at that temperature (Odgerel et al., 2024). These temperature points are defined as A_s (Austenite start), the temperature at which the transformation from martensite to austenite begins when heating. A_f (Austenite finish), the temperature at which the transformation to austenite is finished, above this temperature, all crystals within the allow are austenite. M_s (martensite start), the temperature at which the transformation from austenite to martensite begins upon cooling. M_f (Martensite finish), the temperature at which the martensite transformation is complete, below this temperature, the allow is completely martensite (Martins et al., 2020).

Reciprocating blue Ni-Ti files undergo a proprietary heat treatment once the instrument has been ground to its final shape (Gündoğar & Özyürek, 2017). The objective of this heat treatment is to elevate the A_f temperature within this alloy to be near or above that of the body temperature (37°C) (Odgerel et al., 2024). This thermodynamic shift is the source of the instrument's enhanced clinical properties. By raising the A_f the alloy is engineered to exist in a mixed phase comprising of martensite, R-phase and austenite phase crystals (Almeida et al., 2019). This enhances its mechanical properties, allowing the file to be more flexible and exhibit increased fatigue resistance (Zupanc et al., 2018). During this process, a thin layer of titanium oxide is formed on the surface as discussed above.

The phase transformations are crucial for the mechanical properties of the alloy, when used in a clinical setting. This is because most of the root canal treatments are performed within a small range of temperatures, between room temperature and body temperature, as this is the temperature the endodontic files will be in during use (Gündoğar et al., 2019). The *Table 2* shows the phase transformation temperatures of Reciproc blue files.

Table 2

To show the start and finish temperatures of the different phases (authors own work)

Transformation phase	Temperature	Composition within the alloy
Martensite start M_s	37°c	This is the temperature at which the file begins to transform to the more flexible martensite phase, close to body temperature.
Martensite finish M_f	22°c	Reciproc blue exhibits an intermediate R-phase, contributing to its flexibility
R-phase start	34.5°c	Below this temperature, the R-phase transformation is complete.
R-phase finish	20°c	This value is for the original Reciproc file, not Reciproc blue. The Mf for Reciproc blue is not consistently reported in the same manner.
Austenite start A_s	31°c	The file is a mix of austenite and martensite at room temperature.
Austenite finish A_f	43°c	The file becomes more martensitic at body temperature.

The specific composition and heat treatment of Reciproc blue confer excellent properties for clinicians undertaking root canal treatment. This unique combination of characteristics renders the file highly efficient at cutting whilst reducing the risk of both cyclic and torsional fatigue.

Types of Fatigue Failure

Fatigue failure of endodontic files occurs through either torsional or cyclic fatigue (De Pedro-Muñoz et al., 2024). Although the primary focus of this study concerns cyclic fatigue, it is recognised that torsional fatigue may contribute to instrument fracture. It cannot be ruled out that the reason for failure is likely a combination of both cyclic and torsional fatigue (Caviedes-Bucheli, 2025).

As explained above, torsional fatigue occurs when the instrument experiences twisting forces around its longitudinal axis whilst one end remains fixed, and the applied torque surpasses the elastic limit of the material. The file then undergoes plastic deformation and ultimately shear failure (Ribeiro Camargo et al., 2020). This can occur during endodontic treatment when the file meets resistance, such as sclerotic dentine or a narrow canal. If this twisting force becomes excessive, then the instrument may shear (Thu et al., 2020). Several factors can contribute to the amount of torque that the instrument experiences along its length, including the contact area between the file and the canal walls, the instrument diameter, the amount of force applied apically, and the width of the canal preoperatively (Boscornea-Pușcu et al., 2021).

The larger the contact area, and the smaller the width of the canal preoperatively, the higher the chance of torsional fatigue, as the file has a greater stress placed upon it. The more force is applied apically, and the smaller the diameter of the file, the higher the chance of torsional failure, due to the increased amount of torque present, and the lower the ability of the file to resist this force (Orozco-Ocampo et al., 2022). The diameter of the inner core of the file is more indicative of the risk of failure from torsional fatigue than the diameter including the flutes (Liang & Yue, 2022). The cross section of the file also plays an important role in the resistance to torsional fatigue (Nanthaprathip et al., 2025; Zanza et al., 2021).

Cyclic fatigue is the process by which files fracture due to the consequence of repetitive stress cycles within a curved canal (De Pedro-Muñoz et al., 2024b). As the file rotates within a curved canal, it is subject to alternating tensile and compressive stresses (Sung et al., 2014). The part of the file on the outer part of the curve is undergoing tension, whilst the part of the file within the inner curve is undergoing compression (Le et al., 2023). As the file completes a full rotation, a single point on its surface transitions from maximum tension to maximum compression and back again. This can lead to the initiation and propagation of microcracks, usually concentrated at defects on the instrument's surface, ultimately resulting in a brittle fracture without any signs of plastic deformation (Pirani et al., 2011; Roda-Casanova et al., 2021).

For a file fracture to be from cyclic fatigue alone, it needs to be in an environment in which it is freely rotating within a curve. During endodontic treatment, this scenario is almost impossible, as the purpose of the file is to mechanically prepare the walls of the canals. This means that some part of the file is likely in contact with the canal wall, thereby preventing the file from rotating freely (Iacono et al., 2021).

Cyclic fatigue is the consequence of repetitive stresses that are significantly lower than those required for failure in torsional fatigue (Roda-Casanova et al., 2022). Cyclic fatigue is a cumulative process and has been identified as one of the leading causes of instrument separation (Caviedes-Bucheli, 2025). Torsional fatigue is a ‘strength’ based failure as opposed to cyclic fatigue being ‘endurance’ based failure (Pedullà et al., 2022).

For the purpose of this study, we will be focusing on the cyclic fatigue of rotary files. The differences in strain from compression (a negative value) to tension (a positive value) is called the strain range (Cheung & Darvell, 2008). The amplitude of the strain is half of this range (Peters et al., 2021). In material science, fatigue is categorised based on the number of stress cycles a material can endure before it fails. Ni-Ti endodontic files are classified as having ‘low cycle fatigue’, where the number of cycles before the material fails is lower than 10,000 cycles (Cheung & Darvell, 2008).

For context, typical endodontic files operate between 200 and 2000 RPM (revolutions per minute), with each revolution constituting one stress cycle when the file rotates through a curved canal (Plotino et al., 2009). The total number of stress cycles during endodontic treatment is modest compared to other rotating machinery. For example, if a file is actively used at 500 RPM for one minute, it will undergo 500 stress cycles. However, unlike components in other mechanical systems that may experience lower strain amplitudes, endodontic files undergo exceptionally high strain amplitudes due to the curvatures present within the canal system (Cheung & Darvell, 2008). This strain amplitude can range between 2.5% to 15%, which is considered high for a metallic material and contributes significantly to fatigue failure (Pruett et al., 1997). A mean number of cycles will ultimately lead to file separation (Plotino et al., 2009).

There is currently no agreement as to the most common cause of instrument separation, with studies showing conflicting results (Orozco-Ocampo et al., 2024; Pedullà et al., 2016). It also appears that increasing the torsional resistance of an endodontic file makes it more susceptible to cyclic fatigue and vice versa (Park et al., 2010). It is likely that, in most, if not all, cases of endodontic treatment where a file fractures, both torsional and cyclic fatigue play a role.

Ni-Ti files often fail without warning, even though, due to torsional fatigue, they may exhibit signs of unwinding and plastic deformation, and upon inspection, can be discarded. However, when undergoing cyclic fatigue, there is usually no external sign of plastic deformation to warn of the accumulating damage (Dioguardi et al., 2024). For torsional failure, the torque experienced by the file can cause unwinding, straightening and twisting of the file. This is due to the slipping of the crystalline structure as the elastic limit of the in instrument is exceeded. If the ultimate tensile strength is breached, then the instrument will shear off within the canal (Zanza et al., 2021).

Behaviour of Ni-Ti Under Cyclic Loading

While the behaviour of Ni-Ti under simple, one-directional tensile stress is well-understood, predicting its performance under complex and repetitive loading cycles is far more challenging (Lima et al., 2021). This unpredictability explains why the failure of Ni-Ti instruments in endodontics can often seem sudden and unexpected (Abdellatif et al., 2024; Abushanan et al., 2025).

This type of failure, known as low cycle, high amplitude fatigue, is typical when the stresses on the instrument reach the plateaus of the stress-strain curve. These plateaus represent either the creation of martensite under stress (stress-induced martensite) or the realignment of the existing martensite crystals within the material (Lima et al., 2021).

During cyclic loading, it has been observed that the material deforms more during the initial tension phase than it recovers during the following compression phase (Ding & Zheng, 2023). With continuous cycling, this can result in an accumulative tensile offset, causing the instrument to deform permanently (Xie et al., 2024). This can indicate a fundamental change within the microstructure of the material.

When tested under controlled conditions with a constant amount of bending, the material’s hysteresis loop narrows with each cycle, while the peak stress it experiences increases. (Lima et al., 2021). A hysteresis loop is the graphical representation that shows the relationship between the stress applied to a material (force) and its resulting strain (deformation). These environments are encountered by endodontic files within a curved root canal. Under these conditions, thermally treated Ni-Ti demonstrates enhanced fatigue resistance. This improvement is attributed to the reduced stress required to reorient existing martensite crystals, rather than inducing the formation of new martensite from austenite (Zupanc et al., 2018). The material also undergoes cyclic hardening, which reduces the amount of Ni-Ti available for the phase transformation (Sánchez et al., 2024). It has also been noted that the cyclic fatigue resistance is greater when the material is tested at temperatures between the A_s and A_f (Tao et al., 2024).

Mechanism of Cyclic Fatigue Failure

Finite Element Analysis (FEA) is a computational tool used to predict how stress is distributed within an instrument during use (Saxena et al., 2016). It creates a mathematical model based on various factors, such as the instrument's geometry, material properties and loading conditions. It utilises this model to pinpoint the precise points of concentrated stress (Trivedi, 2014). It has been confirmed that using this model, the fracture point of the instrument is located near the location of the maximum stress, and the higher the curvature of the canal, the more accurate the FEA model becomes (Basheer Ahamed et al., 2018).

The way the endodontic file is manufactured also plays a key role in crack propagation. Ni-Ti files created by the grinding process can have surface defects introduced, such as microcracks and grooves (Mohammadi et al., 2014). These artefacts act as points of stress concentration, making these regions sites for crack initiation (H. C. Kim et al., 2010). The mechanical grinding can also create areas of work hardening on the file's surface, making the material more brittle (Chan et al., 2023). With Reciproc blue, the blue TiO layer provides an important advantage. The oxide layer helps to effectively smooth over microscopic grooves and cracks, thereby reducing stress concentration points and increasing the resistance to crack initiation (De-Deus et al., 2017).

Once a crack is initiated, its path is heavily influenced by the surface features (Matheus et al., 2007). Cracks tend to follow straight grooves left by the machining process, as these can provide an easy path, thereby accelerating failure (H. C. Kim et al., 2010). Cracks typically occur in two stages; initially, the crack propagates across the brittle, defect laden surface (Cheung & Darvell, 2007). Once the crack grows large enough, the remaining core of the instrument can no longer resist the load and fails suddenly in a ductile manner (Lee et al., 2007).

The internal crystalline structure of the material is critical in resisting crack progression. In austenite, which exists in a single-crystalline form, cracks tend to be long and unbranched, resulting in stress remaining concentrated at the tip of the crack, leading to rapid crack progression (Sgambitterra et al., 2021; Zupanc et al., 2018).

However, in martensite, crack propagation is more complex. Due to the different martensite variants, the crack is forced to split into a network of highly branched micro-cracks. This process dissipates the energy that would otherwise drive the crack forward, slowing the crack's progress (Shim et al., 2017). This explains why the modern thermo-mechanically treated files, which are predominantly martensitic, exhibit greater fatigue resistance compared to the traditional Ni-Ti files.

Reciproc blue and RC-Pro blue

Research continues to explore the nuances of Ni-Ti file design to improve clinical performance and safety. A study in 2020, by an Italian research team investigated the influence of the cross-sectional geometry of an endodontic file on cyclic fatigue resistance. The researchers compared files from the same manufacturer that differed only in their cross-section, hypothesising that an S-shaped cross-section design would be more resistant to cyclic fatigue due to reduced metal mass (Di Nardo et al., 2020; Gambarini et al., 2020). However, the study's findings were not conclusive, and further investigation is still required.

Comparative studies between leading brands of endodontic files have also given mixed results. In 2017, a study found that hyflex EDM had superior cyclic fatigue resistance compared to Reciproc blue; however, subsequent research has yielded more ambiguous results (Gündoğar & Özyürek, 2017). A key variable appears to be temperature. It has been shown that the fatigue resistance of Reciproc blue decreases at body temperature (37°C) compared to room temperature (Gündoğar et al., 2019; Vieira et al., 2020). In contrast, the performance of hyflex EDM appears to be more stable across thermal conditions (La Rosa et al., 2023). This temperature difference may account for the mixed results seen across various comparative studies.

A significant recent development in endodontics is the availability of lower cost "replica" files, often manufactured in China. One such example is the RC Pro Blue system. It is marketed as having identical characteristics to the original Reciproc blue (dos Reis et al., 2023; Tarragó, 2025). This has prompted new research into these claims.

A study in 2023 from Brazil provided a valuable early snapshot. The study compared the original Reciproc blue file with four different Chinese replica file systems, assessing both the cyclic fatigue resistance and the surface quality finish via a scanning electron microscope. Interestingly, this study found that the cyclic fatigue resistance of the replica systems was on average very similar to that of the original Reciproc blue files (dos Reis et al., 2023).

Whilst this study was foundational, further research has added crucial layers of understanding. The performance of these replica files in simple single curved canals can be similar to that of Reciproc blue; however, more variability has been observed in more complex double curvature canals (Tarragó, 2025). Whereby the original Reciproc blue files have been found to have a higher resistance to fracture (Tarragó, 2025).

Furthermore, research has also shifted from the average performance of the replica files to performance predictability. It has been shown that even when the mean fracture time of some replica files is comparable to that of the originals, their results exhibit significantly higher variability (dos Reis et al., 2023; Ríos-Osorio et al., 2025; Uslu et al., 2023). This means that some replica files fail unpredictably early, often linked to a higher incidence of surface defects and manufacturing inconsistencies, as observed through SEM analysis.

Recent systematic reviews (2024-2025) indicate that replica systems, despite occasionally demonstrating adequate performance, consistently exhibit more manufacturing defects and greater performance variability compared to their original brand counterparts (Madytianos et al., 2023; Ríos-Osorio et al., 2025; Tarragó, 2025; Uslu et al., 2023). This disparity is likely attributed to the centralised and strictly controlled manufacturing processes of original brands, which contrast with the decentralised production of replica systems across multiple factories. This fragmented manufacturing approach leads to greater inconsistencies and, consequently, more variable product performance.

Testing for cyclic fatigue

Assessing the cyclic fatigue resistance of endodontic files is a crucial area of research in endodontics, driven by the clinical need to mitigate the risk of instrument separation within a root canal system. Instrument fracture is a significant procedural complication that can compromise the treatment outcome (Fan et al., 2025). Consequently, most studies evaluating cyclic fatigue resistance employ a reproducible apparatus that simulates the stresses a file experiences within a curved canal (Plotino et al., 2009). The primary purpose of this apparatus is to allow for a direct and repeatable comparison between different file systems and by reducing the number of confounding variables inherent when using natural human teeth, where there is differing anatomy, curvature and diameter of the canals present (Plotino et al., 2009; Pruett et al., 1997).

To create a reproducible, curved simulated canal, various methods have been employed. These different models range from curved metal or glass tubes to precisely milled metal blocks containing a standardised canal or arrangements of stainless steel pins that guide a file along a specific radius of curvature. While methods involving custom-made tubes or milled blocks offer high precision, the use of pins is often more accessible and cost effective (Pirani et al., 2011; Pruett et al., 1997).

In a typical experiment, a file is secured to the apparatus at a predetermined angle and position, at a set distance, to create a consistent curve. The file is then activated by an endodontic motor and can rotate freely until failure occurs (Bürklein et al., 2021; Pirani et al., 2011; Pruett et al., 1997).

The primary quantitative record in these experiments is the time to fracture, usually measured in seconds from activation until an audible or visible break in the instrument occurs (Gambarini, 2001). Many studies also measure the length of the separated instrument, providing additional data on the fracture location along the files shaft (Bürklein et al., 2021).

Beyond the purely quantitative data, some studies have also incorporated SEM analysis. This provides a qualitative understanding of the fracture mechanism by allowing detailed examination of the fractured surfaces (Martins et al., 2022). It can help reveal characteristic features of cyclic fatigue, such as microcracks, and an area of the final ductile fracture, helping to determine the microscopic cause of the failure (Yum et al., 2025).

Despite their utility for simulated canals for standardisation, it is critical to acknowledge the limitations of these models. Simulated canals, made from glass or metal, possess fundamentally different material characteristics compared to the dentine present within canals (Abushanan et al., 2025). The artificial canals also fail to replicate the complex clinical environment during the root canal procedure, which can include fluctuations in temperature, the use of irrigants, the accumulation of debris, and differences in the operator (Abushanan et al., 2025).

The use of SEM is also not a panacea. Whilst it can identify cracks and structural defects, it cannot provide a complete picture. A file may exhibit stress induced microcracks under an SEM but not go on to fracture. These models, therefore, provide a simplified simulation but cannot fully account for the complex multi-factorial stresses placed upon the file during root canal treatment (Alapati et al., 2005).

However, due to a lack of other avenues, testing for cyclic fatigue resistance in a controlled, reproducible manner is clinically relevant (Bürklein et al., 2024). A file with high cyclic fatigue resistance is less likely to fracture in a severely curved or long canal, thereby directly reducing the incidence of file failure within the canal and leading to better outcomes in root canal treatment (Hülsmann et al., 2019).

The growing availability of replica endodontic files has created a clear gap in current research. There are no published studies that measure the effectiveness or durability of these new files, nor are there any direct comparisons with the original systems they imitate. A review of the existing literature reveals an abundance of studies on the original Reciproc blue files, but a notable lack of data on the RC-Pro blue. This proposed research will provide the first direct comparison between these files. This is especially important as the RC-Pro blue files are significantly cheaper, and clinicians require reliable data on their performance before adopting them in practice.

Research design

Theological Basis

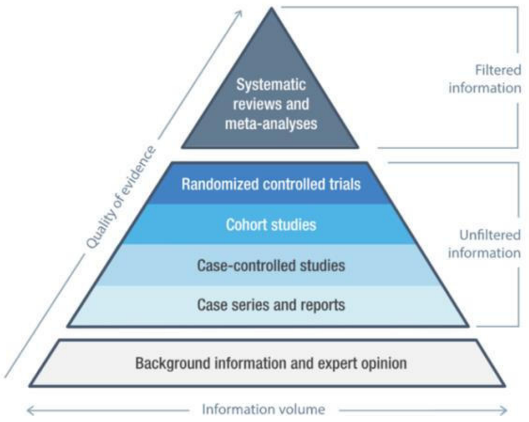
The hierarchy of evidence demonstrates the relative strength and quality of different research methodologies, with systematic reviews and meta-analyses representing the highest level of evidence, followed by randomised controlled trials, cohort studies, and case-controlled studies (Patino & Ferreira, 2018). This categorisation helps researchers understand the reliability and applicability of different study designs when contributing to evidence-based practice.

For this investigation, understanding the position of experimental studies within this hierarchy is crucial, as it informs both the methodology and the potential impact of the findings. Case-controlled studies, such as this experiment, while not at the apex of the evidence hierarchy, provide valuable comparative data when examining specific variables under controlled conditions (Krivicich et al., 2023). This is particularly relevant when comparing the mechanical properties of endodontic instruments, where precise control of testing conditions is essential for reliable results.

The current study is a primary experimental research study in which the author will collect and record the data. Hence, to design an experimental study for evidence-based practice, it is important to be aware of the hierarchy of different evidence (Hoffmann, T., Bennett, S., & Del Mar, 2017). An example of this hierarchy is shown in Figure 8.

Figure 8

The hierarchy of evidence, top-down approach for locating the best form of evidence (University of Canberra, 2016).



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The experiment can be considered a case-controlled study, in which two independent variables are compared (Krivicich et al., 2023). This study design allows for the direct measurement of cyclic fatigue resistance between the two file systems under standardised conditions, while maintaining experimental control of confounding variables.

Furthermore, the two main methods of conducting research are quantitative and qualitative. Quantitative research aims to provide generalisable facts under controlled experimental settings (Chai et al., 2021). In quantitative research, the data is described numerically and analysed statistically to test specific hypotheses and establish causal relationships within large population samples. This methodology is particularly effective when examining measurable variables.

Conversely, qualitative research seeks to identify objective meanings of a phenomenon (Newton, 2000). This approach focuses on developing theoretical frameworks and understanding complex processes through detailed observation and analysis. Such methodology is valuable when exploring decision-making processes or investigating communication patterns in clinical settings.

Most research within dentistry has been conducted using quantitative methodology (Chai et al., 2021). This prevalence is due to the field's emphasis on evidence-based practice and the need for reproducible, measurable outcomes. In quantitative research, data is obtained under controlled experimental conditions to produce quantifiable answers to research hypotheses (Gill et al., 2008).

For the purpose of this study, testing the hypotheses requires measuring the time taken for each file to fracture under controlled experimental conditions. The study will generate objective, quantifiable data for comparison between the two file systems. Hence, this study employs a quantitative research approach to investigate the cyclic fatigue resistance of Reciproc blue and RC-Pro blue endodontic files.

Study Design

This study employs a between-groups design in which the researcher will examine two independent groups/variables (Reciproc blue and RC-Pro blue files) against the dependent variable (time to file fracture in the testing apparatus). This experimental design enables a direct comparison of cyclic fatigue resistance between the two file systems under controlled conditions, as explained in the section on instruments and apparatus below.

The use of a standardised testing apparatus ensures the reproducibility of the study design. The measurable nature of the fracture time, coupled with the reproducibility of the experimental setup, positions this study firmly within the realm of quantitative research.

Sample Size and Selection

A review of the existing literature was conducted to identify studies with comparable experimental designs that investigate the cyclic fatigue resistance of endodontic files. Particular attention was given to studies evaluating Reciproc blue files using a testing apparatus with a 60° curvature in the apical 5mm of the file. Two studies, both from 2018, were chosen to help with the identification of the sample size: Cyclic fatigue resistance of new reciprocating files (Reciproc blue, WaveOne Gold, and SmartTrack) in two different curved canals and Cyclic Fatigue of Reciproc® and Reciproc blue Nickel-titanium Reciprocating Files at Different Environmental Temperatures (Plotino et al., 2018; Topçuoğlu et al., 2018). The approximate fracture times and standard deviations reported in these studies were recorded and used as input parameters for sample size calculation.

To determine the appropriate sample size for this study, a statistical power analysis was performed using the G*Power software (Faul et al., 2009). The concepts for the statistical power analysis were covered in Discovering Statistics Using IBM SPSS and applied to the software G*Power (Field, 2018). The following parameters were imputed (see appendix III):

- Significance level (α) = 5%
- Power (1-β) = 95%
- The approximate average time for fracture at room temperature: 400 seconds for Reciproc blue
- Due to the absence of published data on the cyclic fatigue resistance of RC-Pro blue endodontic files, an educated estimate was made for the average fracture time. Based on the similarities in design and manufacturing between RC-Pro blue and Reciproc blue, a fracture time of 350 seconds was chosen as a reasonable approximation for RC-Pro blue.
- Standard deviation = 20 seconds

Based on these input parameters, the power analysis yielded a total sample size of 12 files, with 6 files allocated to each group: Reciproc blue and RC-Pro blue.

Calculating the minimum sample size ensures that the study is adequately powered to detect significant differences in the cyclic fatigue resistance between the two file systems (Field, 2018). By incorporating the average fracture time and standard deviation reported in previous studies, this approach enhances the reliability and validity of the current study's findings (Serdar et al., 2021).

The sample size of 12 files, evenly distributed between the Reciproc Blue and RC-Pro blue groups, provides a foundation for the comparative evaluation of their cyclic fatigue resistance.

The use of data from previous research can introduce a level of uncertainty when estimating sample sizes for current studies (Serdar et al., 2021). This uncertainty arises due to potential variations in study design between the previous studies and current experiment. Both studies conducted by Plotino et al. (2018) and Topçuoğlu et al. (2018) were used to determine the sample size for evaluating the cyclic fatigue resistance of Reciproc blue and RC-Pro blue endodontic files (Plotino et al., 2018; Topçuoğlu et al., 2018).

Although both prior studies provided comprehensive descriptions of the file parameters, they did not include detailed information about the testing apparatus itself. This lack of detail may suggest that both experiments may not have been standardised, and their results may potentially limit their applicability to the current experiment. If the present investigation employs a different method, the figures derived from previous studies may not be entirely suitable for precise sample size estimation (Hickey et al., 2018; Riaz Malik et al., 2022).

These disparities in experimental conditions can impact the reliability and validity of the results (Riaz Malik et al., 2022). To mitigate potential inconsistencies, researchers conduct pilot studies to generate data specific to their experimental setup. This approach can provide more reliable estimates of the required sample size and enhance the robustness of the study design (Field, 2018).

Validity

To investigate the fatigue resistance of endodontic files, studies focus on simulating conditions found within the clinical environment. The cyclic fatigue resistance is measured as the number of rotations to failure or the time to failure of the endodontic files. The parameters of the experiment are described by a specific angle and radius of curvature which is a constant for all the files. Through these simulated conditions, researchers attempt to establish the superiority of endodontics instruments under very controlled conditions. The data gathered can then be used to make more informed decisions when using these instruments clinically (Plotino et al., 2009).

However, it is essential to recognise that confounding variables exist in these experiments. Due to the intrinsic differences between endodontic instruments, ranging from the design and flexibility to the recommended settings used to operate the file, a completely unbiased comparison is difficult to gain (Hülsmann et al., 2005).

In this experiment, the experimental design and the chosen files were aimed at limiting confounding variables and ensuring strong internal validity. Although the number of confounding variables will be reduced as much as possible, it is important to recognise that increasing the internal validity of the experiment may reduce the external validity of the research, and it may not be as clinically relevant (Grimes & Schulz, 2002).

In this experiment, the author intends to compare the cyclic fatigue of Reciproc blue files with a Chinese copy file, RC-Pro blue. Although Reciproc blue's performance has been well-documented, there are no studies for the RC-Pro blue files. The claims made by the distributor of the RC-Pro blue files are that they are identical copies of the Reciproc blue; however, these are impossible to verify without experimenting.

Lacking the specialised equipment required to measure and compare the key features of Reciproc blue and RC-Pro blue, such as file taper, cross-sectional design and flute architecture, the manufacturer's claims for RC-Pro blue cannot be confirmed. The potential differences in the manufacture of the RC-Pro blue may lead to significant variations in the results. One of the concerns is that the RC-Pro blue files have the same heat treatment as the Reciproc blue files, which could impact the flexibility and durability of these files. They may also contain more variation if the same strict manufacturing process used for Reciproc blue is not the same, resulting in more variation in the results.

The apparatus used for testing cyclic fatigue can itself introduce confounding variables. The precise path the endodontic file takes during testing can give rise to variations in the test outcomes (Pedullà et al., 2018). Even minor deviations in the path of the file can produce inconsistent results, which may be why results vary across different cyclic fatigue studies within endodontics (Hülsmann et al., 2019; Pedullà et al., 2013).

Unless instruments are strictly constrained to a uniform trajectory, the inherent flexibility due to its cross-sectional design and heat treatment may allow each individual file to navigate the test canal differently. This variance means that each individual file may be subjected to varying maximum amounts of strain on different parts of the file, thereby altering the test conditions and affecting the results (Hülsmann et al., 2019).

Temperature is also a relevant factor when conducting a cyclic fatigue test, especially with NI-TI endodontic files. This is due to the different crystalline phases within the file. Due to this, the mechanical properties of the file change with different temperatures. Studies on cyclic fatigue resistance are typically conducted at either room temperature or body temperature (Klymus et al., 2019).

The rotational speed of the instrument within the simulated canal is also very important. It is imperative to use the manufacturer's recommended settings to ensure that the results are clinically relevant and standardised (Lopes et al., 2009).

Reliability

It is important for the experiment to be as reliable as possible to help ensure that results are as reproducible as possible. The selection of the endodontic motor was essential for standardising the experiment. The Dentsply X-Smart Plus motor was chosen due to its integrated preset for the Reciproc blue file system, which ensures that the file operates at the manufacturer-specified reciprocating angles, speed and torque. The use of this preset provided a consistent and standardised motion for all the files tested.

The time taken to fracture was hand-timed. The author used his phone to record the timings and used his thumb for every start-stop, minimising further human error. This was for practical considerations, with the time taken measured in the nearest second. This stopwatch was started in time with the footswitch being activated. The stopwatch was stopped once there was an audible or visual confirmation that the file had failed. The reliability of this was increased as the author was the person starting the endodontic motor and the stopwatch at the same time.

The reaction time and human error is a potential cause for a lower reliability for the experiment. However, since the author undertook the tests on all the files, the degree of human error can be considered the same for all the files, therefore have a negligible effect on the outcome of the experiment.

Whilst a completely randomised study design would be the most appropriate for this experiment, practical limitations prohibit this. Ideally file selection would be randomised across different suppliers and lot number to simulate clinical procurement by clinicians. However, such a design is not feasible, as the availability of RC-Pro blue is restricted to a single supplier within the United Kingdom, unlike the widely available Reciproc blue. The acquisition method for purchasing files mirrors the process used by clinicians when ordering from online suppliers. Consequently, the sample of files can be considered representative of the files available for general use.

A pilot study with a small sample size can be used to help select an appropriate sample size for the main study, thereby increasing the power of the experiment and allowing a better chance of finding a statistically significant result (Thabane et al., 2010). However, a pilot study was not conducted in this experiment as the author did not want to limit the test sample size by using available files for a pilot study.

Hypotheses

The hypothesis of this experiment is: Reciproc blue will take longer to fail than RC-Pro blue. This will be tested with a 95% level of significance.

Equipment

Equipment used for this study were:

- 6 files Reciproc blue
- 6 files RC-Pro blue
- Apparatus: wooden block with pins as mentioned below
- Honigum dental impression putty
- Dentsply xSmart plus endodotic motor
- Pen / paper to record
- Stopwatch on Mobile phone

Experimental Method

Six Reciproc blue R25 files and six RC-Pro blue R25 files were ordered from DentalDirectory and UKdentistry.co.uk respectively.

The apparatus was made by the author with a schematic for the file made on the website desmos.com/geometry. The design was printed and used as a template to place the pins within the wooden block. The pins were placed to help create a 60° curve. The first pin was placed in a straight line perpendicular to the motor at 6mm, followed by the second pin on that line at 16mm. A third pin offset to give the radius at the apical position of the file was placed at 21mm. The arc of the radius is 4.77mm. This allowed the file to curve at the desired curvature for this experiment.

It is important for the experiment that the author was able to reproduce the trajectory of the file for each file used. For this purpose, the endodontic motor was then secured to the apparatus using dental impression putty. The file was inserted into the motor and positioned in the desired location within the apparatus. The motor was then held in place while dental putty was placed around it, creating a snug fit that also allowed for easy removal. Once the putty hardened, the motor was removed and replaced, ensuring that both the file and motor seated back in their original position. Since both files were the same length, there was no need to adjust the motor's position between different file types. The fixed position of the putty helped keep the motor and files in the same position every time. As the impression putty was moulded around the motor, it ensured that the motor could be placed back into the same position after each file was tested. One of each file type was then tested with the new apparatus setup to ensure a good fit and consistency. See Appendix I for pictures of the experimental setup.

The room temperature was controlled at 21°C using a Mitsubishi wall mounted air conditioner, set at auto and low speed. The room was then left with this setting for 4 hours to ensure that the temperature was stable upon commencing the experiment. The experiment was conducted in a portion of the room where no direct air was blown by the air conditioner. All the materials for the experiment were left in the room as it acclimatised.

The files were tested with the position of the rubber stop at the highest point of the file and flush with the beginning of the wooden block. This was verified by the author of the study.

The time to fracture was then recorded by the author. The time was recorded and rounded to the nearest second with a digital stopwatch on the author’s mobile phone. See Appendix II for the raw data. The data was recorded on an Excel sheet and saved on the author’s computer, and online on OneDrive to prevent data loss.

Results

Data analysis

The purpose of this study is to compare the time to fracture for Reciproc blue and RC-Pro blue files, to test their cyclic fatigue resistance. Samples of RC-Pro blue and Reciproc blue (6 files for each) were tested till failure.

Using SPSS software, standard statistical tests to compare means such as t-tests for parametric data or Man-Whitney U tests for non-parametric data were considered depending on the distribution of the data.

Descriptives

The time taken for the files to fracture was converted from minutes and seconds to seconds before being inputted into SPSS. The t-tests were all 2-tailed and the significant p-values are recorded.

The descriptive statistics have been generated as can be seen in Table 3. From this table it is observed that the mean time in seconds for RC-Pro blue (209 seconds) is longer than for Reciproc blue (103 seconds).

In order to statistically compare both the means for Reciproc blue and RC-Pro blue, it is essential to make several key assumptions, such as the data qualifying the tests for normality and homogeneity of variances.

Table 3

Descriptive statistics of the data

Descriptives				
File			Statistic	Std. Error
Time Taken seconds	Reciproc blue	Mean	103.833	11.9007
		Median	96.000	
		Variance	849.767	
		Std. Deviation	29.1508	
		Minimum	77.0	
		Maximum	159.0	
		Skewness	1.716	.845
		Kurtosis	3.344	1.741
	RC-Pro blue	Mean	209.000	19.1398
		Median	219.500	
		Variance	2198.000	
		Std. Deviation	46.8828	
		Minimum	121.0	
		Maximum	257.0	
		Skewness	-1.605	.845
		Kurtosis	3.275	1.741

<u>Normality</u>

Firstly, the objective was to determine if the data is normally distributed and then to assess a statistically significant difference between the two file systems. For small sample sizes, like the six observations for each file system in this experiment, the Shapiro-Wilk test is considered the most powerful and reliable method. The Shapiro-Wilk analysis revealed that the data for both the Reciproc blue (p=.128) and RC-Pro blue (p=.183) file systems can be considered conceivably normally distributed since p> 0.05. This finding allows for the use of a parametric test, such as the independent samples t-test.

Table 4

Tests of normality

Tests of Normality

		Kolmogorov-Smirnov[a]			Shapiro-Wilk		
Time Taken (seconds)	File	Statistic	df	Sig.	Statistic	df	Sig.
	Reciproc blue	.263	6	.200*	.839	6	.128
	RC-Pro blue	.282	6	.146	.858	6	.183

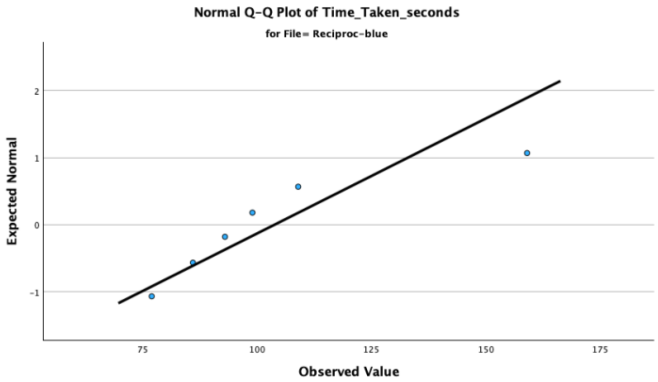
*. This is a lower bound of the true significance.

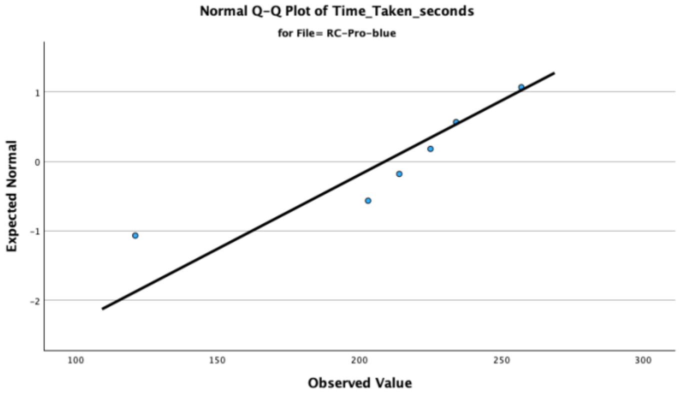
a. Lilliefors Significance Correction

The Q-Q plot can be used to graphically represent how close a continuous data set corresponds to a normal distribution. As observed from the graphs below, the data points are close to the oblique line with few deviations.

Figure 9

Q-Q plots for both file groups: Reciproc blue and. RC-Pro blue

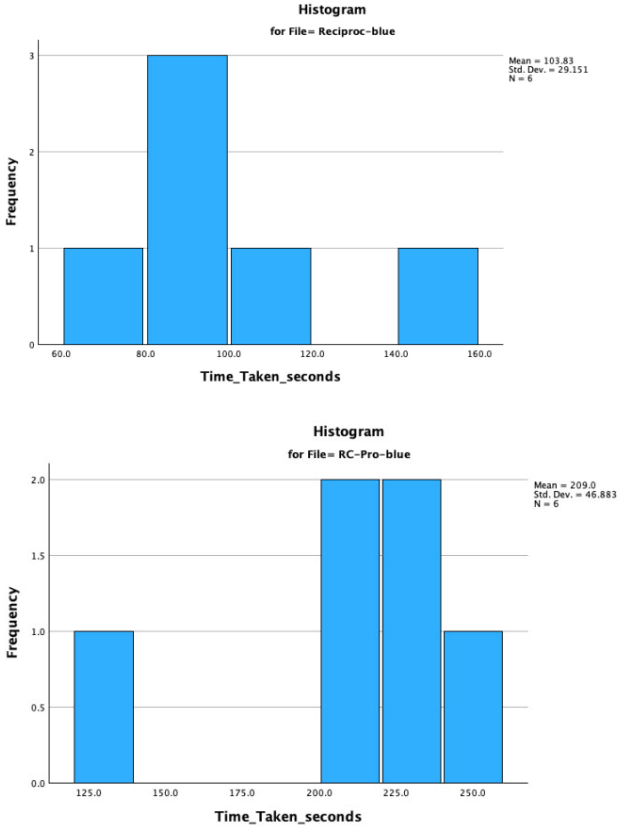




Histograms can be used to evaluate the frequency of data and are a representation of the distribution of the data values. They can help to evaluate the central location, width of spread and shape of the data. SPSS™ can overlay the histogram with a normal plot.

Figure 10

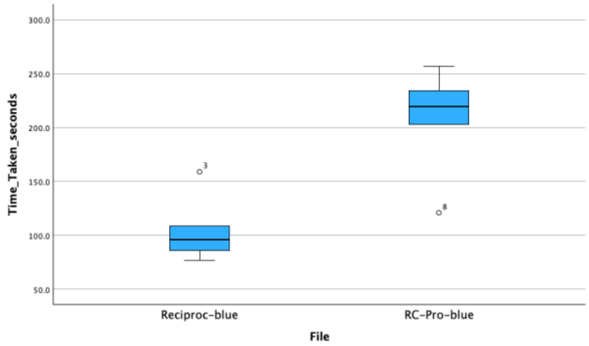
Histograms for both file groups Reciproc blue and RC-Pro blue.



Box plots also visually represent the data distribution. These graphs show characteristics of distribution of data which are: the upper quartile and the lower quartile (start and end of the box respectively), median (middle line across the box), “whiskers” on box plots are the maximum and minimum values used as endpoints for the whiskers, and lastly the outliers, represented by a mark (circle) outside the box.

Figure 11

Box plots for both file groups: Reciproc blue and RC-Pro blue.



Based on both descriptive and inferential statistics of tests of normality, the data is considered to conform to normality.

Homogeneity of Variances

Homogeneity of variance means the two groups being compared are assumed to come from populations with equal variances. If this assumption is violated, where the variances of the two groups are significantly different—then results of the standard t-test may be unreliable or inaccurate.

Hence, a Levene's test was observed which is a formal statistical test specifically designed to assess whether the variances of two or more groups are equal. Levene's test indicated that variances were homogeneous (F(1, 10) = 0.546, p = .477).

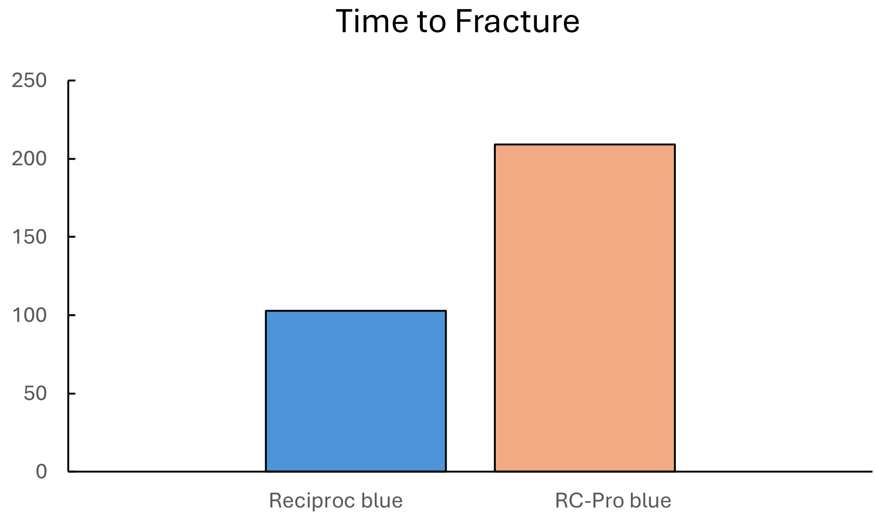
T-test

An independent samples t-test was conducted to compare the difference between the time taken to fracture in seconds for both files, Reciproc blue and RC-Pro blue, with a one-tailed hypothesis that the Reciproc blue file system would exhibit a longer time-to-fracture than the RC-Pro blue system. The assumption of equal variances was met. Therefore, the results from the "Equal variances assumed" row of the t-test table were used for interpretation. The results revealed a significant difference between Reciproc blue files and RC-Pro blue files; $t(10)=-4.66$, $p<0.001$.

Furthermore, the results reveal that the mean time-to-fracture for the RC-Pro blue (M = 209.0 seconds, SD = 46.9) group was significantly higher than for the Reciproc blue group (M = 103.8 seconds, SD = 29.2) with a mean difference of -105.17 seconds. which is the opposite of the predicted direction.

Figure 12

Graph demonstrating the mean time to fracture for both file groups Reciproc blue and RC-Pro blue.



Effect Sizes

To understand the magnitude of the difference between the variables, the corresponding effect sizes were observed. The analysis revealed a very large effect, with Cohen's d = -2.69. For the small sample size, a corrected effect size was also calculated, yielding a Hedges' g = -2.49. The large effect size suggests a substantial difference in the time-to-fracture between the RC-Pro blue and Reciproc blue file systems.

Discussion

The results of this study indicate that:

1. There is a difference in the time to fracture within this cyclic fatigue experiment between Reciproc blue and RC-Pro blue.
2. RC-Pro blue files on average took longer to fracture than Reciproc blue.

The findings of this experiment have led to the rejection of the author's hypothesis, which theorised that the Reciproc blue files would experience a longer time to fracture than RC-Pro blue files. Conversely, the results demonstrated that RC-Pro blue files had a significantly longer time to fracture than Reciproc blue, directly opposing the author's hypothesis.

Whilst each group presented with a notable outlier - a rapid time to fracture for RC-Pro blue (121 seconds) and a delayed time to fracture for Reciproc blue (159 seconds)- the overall data sets remained distinct. The RC-Pro blue files consistently demonstrated a longer time to fracture, leading to the conclusion that in the parameters of this experiment that RC-Pro blue possess superior resistance to cyclic fatigue.

The RC-Pro blue group contained an outlier with a shorter time to fracture (121 seconds), whereas the Reciproc blue group included an outlier with a longer time to fracture (159 seconds). Barring these outliers, RC-Pro blue files took longer to fracture than all other Reciproc blue files. This can lead to the conclusion that in the context of this experiment RC-Pro blue files will almost always have a longer time to fracture time.

The conclusion that, within the limitations of this study, RC-Pro blue files possess greater cyclic fatigue resistance compared to Reciproc blue is meaningful. As discussed above, cyclic fatigue is a major cause of file separation during root canal treatment, particularly when treating curved canals. Therefore, if a file system has a longer average time before failure, it can provide clinicians with a greater margin of safety during root canal treatment.

Although both files are manufactured from Ni-Ti, and have the same visual appearance, the exact ratio of the metals is proprietary and can vary between manufacturers. These subtle differences in the metallurgical composition can significantly alter the alloys' crystalline structure and phase transformation temperatures and behaviour. This is fundamental to the file's flexibility and its ability to resist the formation of cracks. The longer time to fracture of RC-Pro blue is strongly indicative of the fundamental differences in the metallurgy or heat treatment of this file which is different to that for Reciproc blue.

Limitations

There are many limitations to this study which must be clarified, to ensure future studies can enhance and refine the experiment to have better internal and external validity.

One aspect is the apparatus used to test the files. The apparatus is made from wood with metal pins placed to help shape the path of the file to a desired curvature. This method of making the apparatus is relatively imprecise, as there is an element of human error. As this was created by the author and not by an automated machine, there may be errors in the placement of the pins and the exact curvature produced by the file once inserted.

The motor is held securely in place with dental putty to help ensure the reproducibility of the file insertion. However, this may not be the most reliable setup; a milled artificial canal and a more robust mechanism to hold the motor in place may provide more reliable results, but due to practical and financial constraints, using pins was the best available method. Due to the flexible nature of the putty, there is a risk that the insertion of the file could have changed over the course of the experiment. These limitations affect the internal validity of the study and should be taken into account when recreating this experiment.

Pertaining to the external validity of the experiment, there are also areas of note. The first is that the apparatus used to create the curvature for the file is dissimilar to a root canal, and therefore, the results cannot be directly applied to a clinical situation.

There is also the fact that when performing root canal treatment, the file is not only subject to cyclic fatigue but also torsional fatigue, which has not been tested in this experiment. The combination of both these phenomena may not be comparable to the results found in only a cyclic fatigue test.

Within the root canal system, during endodontic treatment, there are also other factors that must also be considered. There is no provision for the effects of any common irrigant used, such as hypochlorite, which may affect the behaviour of the files. The experiment is also conducted in a static position, rather than the pecking motion typically used during endodontic procedures. This may change the results drastically as it may change the parts of the file where the forces are acting the most.

Further Discussion

All endodontic files first start out as blanks which are then processed into their final shape. In the case of Reciproc blue, the file starts out as a blank of M-wire. The exact manufacturing process for RC-Pro blue is not known, but it can be assumed that it is comparable to that of Reciproc blue as per the manufacturer's claims. The M-wire blanks, once ground into the correct shape, undergo a proprietary thermo-mechanical treatment which changes the internal crystalline structure (Pereira et al., 2015). This treatment also provides the blue colour on the outside of the file, a thin layer of TiO (Generali et al., 2020). This surface of TiO is thought to further enhance the ability to resist cyclic fatigue due to its reduction in surface defects and cracks (De-Deus et al., 2017). The thickness of this layer between Reciproc blue and RC-Pro blue could play a role in the difference in the time to fracture of these file systems in this experiment.

The phase properties of the crystalline structure of the Ni-Ti also play a central role in the files ability to withstand cyclic fatigue. The phase transformation temperatures for each crystalline structure for Reciproc blue are described in Table 2. As there is no clinical research for the phase transformation temperatures for RC-Pro blue, this could be another reason for the difference in the time to fracture of this system.

Temperature is a significant factor, as it determines the exact composition of the crystalline structure within the file, which can substantially affect the mechanical properties of the file itself (Klymus et al., 2019; Plotino et al., 2018; Uygun, 2020; Vieira et al., 2020). This is particularly important as there is a small range of temperatures for each crystalline phase.

The flute design of the Reciproc blue is also a factor in the cyclic fatigue resistance of this system. The flute designs enable a smaller core mass, making the file more flexible and resistant to cyclic fatigue (Martins, Silva, Marques, Belladonna, Simões-Carvalho, Vieira, et al., 2021). Specialist equipment would be required to test the flute architecture of RC-Pro blue and Reciproc to determine any differences.

As mentioned in the literature, the Reciproc blue file system has greatly improved its cyclic fatigue resistance as compared to other file systems (Gündoğar & Özyürek, 2017). This was further investigated, and the thermo-mechanical heat treat combined with the unique flute design is what set Reciproc blue apart (De-Deus et al., 2017; Generali et al., 2020). However, there were no clear standardised methods in which these experiments were conducted.

The experiments differed in the type of apparatus used for conducting the cyclic fatigue tests. Some experiments utilised pins, while others employed milled artificial canals in a metal block (Di Nardo et al., 2020; Gambarini et al., 2020; Peters et al., 2021; Plotino et al., 2018; Thu et al., 2020). There was also no set angle or point of curvature for the files, with some of the curves being between 45 degrees and 90 degrees. No set standard has been established as to which portion of the file is subjected to this curve. Due to the lack of conformity in the way the tests are conducted, there is a huge amount of data available, but this is not necessarily all compatible and transferable between experiments and file systems.

With the enhancement of Ni-Ti technology and advances in metallurgical and thermomechanical heat-treatments now available, the risk of iatrogenic errors in endodontics has greatly reduced. The flexibility and super-elasticity allow these new files to be more centred within the canal. This allows the final canal shape to have better irrigation penetration and a better obturation (Grande et al., 2023). These properties have enabled clinicians to better manage more complex and challenging anatomy (Abdellatif et al., 2024).

Recommendations

Due to the small sample size and experimental design, further research would be necessary to confirm this finding. A larger sample size would also be beneficial to reduce the risk of anomalies present within the file batches. Due to financial constraints, the author adopted the current experimental design. In the future, a larger sample size and a more precise apparatus to confine the file may yield more data.

Tests using a milled block with an artificial canal space milled may constrain the file more than the pins used in this experiment. This would reduce the risk of other forces acting on the files.

Temperature is also a variable that can be manipulated by conducting the experiment at different temperatures to see if the results vary. This would enable testing the file with different internal crystalline phases. As has been discussed above, the different crystalline phases can make a substantial difference in the mechanical properties of the files during use.

It is therefore essential that robust research is carried out on new file systems to allow for a more direct assessment of each file systems advantages and disadvantages. Relying on manufacturers claims is not always reliable and unbiased research is key.

Conclusion

The results of this experiment were not what the author expected with the RC-Pro blue files taking longer to fracture than Reciproc blue. However, testing of new files systems is crucial to enable clinicians to provide the best possible treatment for their patients. It increases the number of file systems available in the clinician's armamentarium whilst also allowing the clinicians to be more confident that the treatment they are providing is to the highest standard possible.

This is especially the case between Reciproc blue and RC-Pro blue, where the cost of RC-Pro blue is significantly lower than that of Reciproc blue. This lower cost may allow the root canal treatment to be more affordable and cost effective for patients and clinicians and may lead to patients opting to try root canal treatment over other treatment options. The comparison between Reciproc blue and RC-Pro blue is therefore imperative as this allows the treating clinicians to make an informed choice as to treatment options and outcomes when treatment planning.

As this experiment shows, the more expensive file system does not always perform better in every scenario. New file systems may perform as well or better than their more expensive counterparts, even if these new systems are replicas. Further research would be required to test the RC-Pro blue with different experimental designs to gain a better understanding of the full limitations of this new file system.

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Appendix I

Experimental Setup pictures

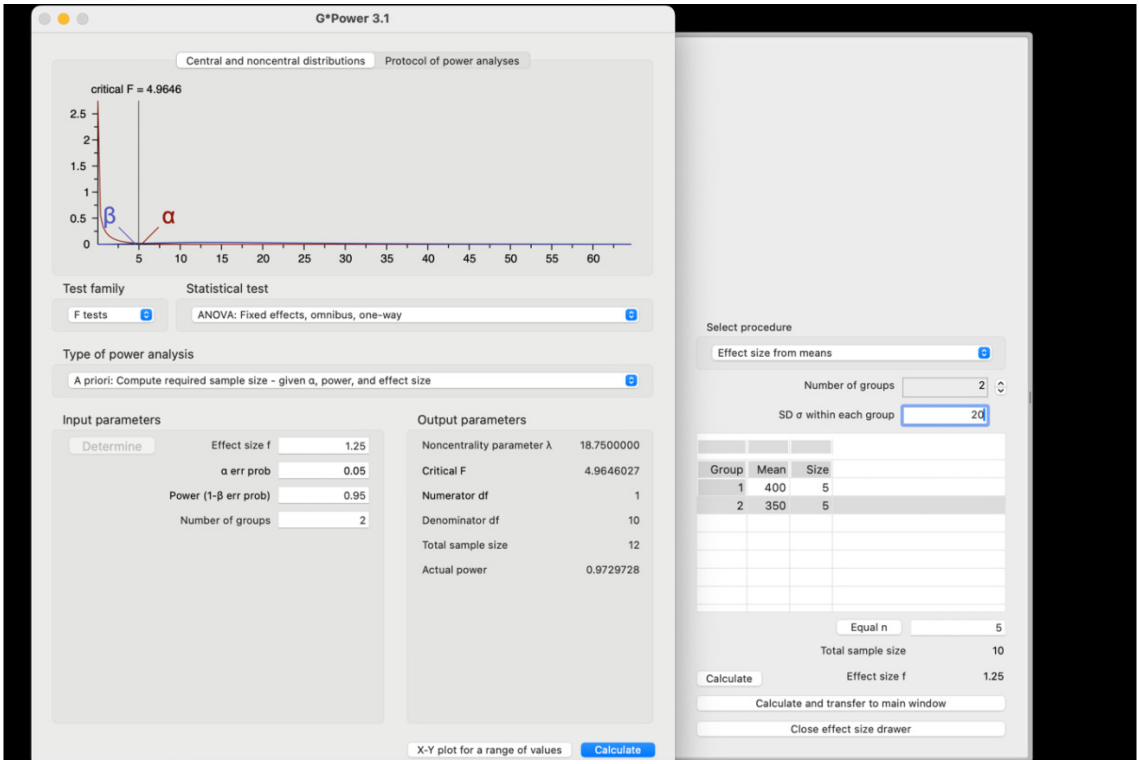
Appendix II

Results raw data

	File system	
Time taken to fracture (minutes and seconds)	Reciproc blue	RC-Pro blue
	1.26	3.23
	1.49	2.01
	2.39	4.17
	1.39	3.45
	1.17	3.34
	1.33	3.54

Appendix III

G-power



Test family: F tests

Statistical test: ANOVA: Fixed effects, omnibus, one-way

Type of power analysis: A priori: Compute required sample size - given α, power, and effect size

Input parameters

Effect size f	1.25
α err prob	0.05
Power (1-β err prob)	0.95
Number of groups	2

Output parameters

Noncentrality parameter λ	18.7500000
Critical F	4.9646027
Numerator df	1
Denominator df	10
Total sample size	12
Actual power	0.9729728

Select procedure: Effect size from means

Number of groups: 2

SD σ within each group: 20

Group	Mean	Size
1	400	5
2	350	5

Equal n: 5

Total sample size: 10

Effect size f: 1.25