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Behavior of NiTi Endodontic Instruments Exposed to Irrigating Solutions and Chelating Agents: A Systematic Review

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Abstract

Objective: The main objective of this systematic review is to study the behavior of NiTi alloy files in the presence of chelating agents and irrigants. This objective will be achieved through specific objectives, namely: a comparative evaluation of the effects of irrigants on the cyclic fatigue of files, a comparative analysis of the effects of irrigants on file topography, and finally a comparison of the effects of irrigants on file corrosion. **Materials and Methods:** This is a systematic literature review for which our literature search was conducted using PubMed and Google Scholar as the main databases. Eligible studies were published in English or French between 2006 and 2023, and included literature reviews, systematic reviews, meta-analyses and laboratory (*in vitro*) studies meeting the inclusion criteria. **Results:** Of the 30 articles identified as meeting the inclusion and exclusion criteria, the study by Pedullà *et al.* (2014) found that immersion in NaOCl did not reduce the cyclic fatigue of reciprocating or continuously rotating NiTi files, whereas EDTA reduced the fatigue resistance of all instruments after 3 minutes; in addition, immersion in surfactant-containing irrigants did not affect the cyclic fatigue of the instruments, with the exception of Reciproc files immersed in a Hypoclean solution. Along the same lines, a scoping review by Orozco-Ocampo and colleagues (2022), synthesizing secondary evidence on fatigue failure of NiTi files, reports that immersion in NaOCl does not appear to affect cyclic fatigue resistance, whereas immersion in EDTA for more than three minutes is associated with a decrease in this resistance. Furthermore, a study by Sağlam *et al.* (2012) concluded that the use of 2.5% NaOCl could be recommended to prevent weakening of the ProTaper file, which shows less surface alteration compared with the use of 5% NaOCl and the MTAD solution. A study by De Castro Martins *et al.* (2006) concluded

that immersion in 5.25% NaOCl for 24 hours did not modify the surface characteristics or the fatigue resistance of the instruments tested, whereas simulated shaping was a determining factor in reducing the number of cycles to failure. Cheung and Darvell (2008) concluded that the rotating-bending fatigue resistance of NiTi rotary instruments is brand-dependent and is influenced by NaOCl, which corrodes NiTi instruments by creating microcracks on their surface. **Conclusion:** This study thoroughly examined the behavior of nickel-titanium alloy files when exposed to various irrigants, focusing in particular on the impact of NaOCl and EDTA solutions. The investigations addressed specific aspects such as cyclic fatigue, potential corrosion and the topographic changes resulting from interactions with different endodontic irrigants. These detailed observations are essential for an in-depth understanding of the complex effects of irrigating solutions on endodontic instruments. The results of this research make a substantial contribution by further clarifying the mechanisms of interaction between NiTi files and irrigants, thus paving the way for significant improvements in clinical endodontic practice. In addition, the study highlights a notable gap in the scientific literature by pointing out the lack of research on the influence of the different forms of EDTA on the behavior of NiTi files. This finding sheds light on a research area that remains largely unexplored, thereby reinforcing the importance and relevance of the present study for the advancement of knowledge in this field.

Subject Areas

Dentistry

Keywords

Cyclic Fatigue, EDTA, Nickel-Titanium, Sodium Hypochlorite, Surfactant, Lubricant, Corrosion, Surface Defects, Instrument Fracture, Microcracks

1. Introduction

Modern endodontics has seen major advances with the introduction of nickel-titanium (NiTi) instruments. Thanks to their superelasticity, shape memory and greater flexibility compared with conventional stainless steel instruments, NiTi files make it easier to prepare curved root canals and help maintain their anatomical path. However, despite these advantages, instrument fracture remains a potential complication, notably because of cyclic fatigue, torsional stresses and surface alterations.

The effectiveness of endodontic treatment also depends on canal irrigation, which complements mechanical instrumentation by removing debris, disinfecting the canal and managing the smear layer. Sodium hypochlorite (NaOCl) is mainly used for its antimicrobial activity and its ability to dissolve organic tissue, whereas chelating agents, such as ethylenediaminetetraacetic acid (EDTA), contribute to removing the inorganic component of the smear layer by demineralizing the den-

tin. However, exposing NiTi instruments to irrigating solutions can lead to changes in their surface and mechanical properties. Depending on the nature of the irrigant, its concentration, pH, temperature and the duration of exposure, these solutions may be associated with corrosion, surface erosion, microcracks or changes in cyclic fatigue resistance [1].

The aim of this study is to improve our understanding of the behavior of NiTi files in the presence of chelating agents and disinfectants, and then to examine the factors likely to affect this interaction. To this end, we set the following objectives: to evaluate the behavior of NiTi files after exposure to various chelating agents and irrigating solutions, and to analyze their influence on corrosion resistance, surface changes and the mechanical properties of NiTi instruments. A better understanding of these interactions could help guide the choice of irrigation protocols and improve the safety of canal preparation.

This review was guided by the following PECO question: in nickel-titanium endodontic instruments (Population), does exposure to sodium hypochlorite and/or chelating agents such as EDTA, alone or combined with surfactants (Exposure), compared with no exposure, saline solution or another irrigating solution (Comparator), modify cyclic fatigue resistance, surface topography and corrosion resistance (Outcomes)? Eligible study designs included experimental laboratory (*in vitro*) studies, as well as systematic reviews, scoping reviews and meta-analyses addressing this question.

2. Methodology

This is a systematic literature review describing the behavior of NiTi files in the presence of chelating agents and irrigants, comparing and discussing the results of scientific publications on this topic. First, a computerized search was conducted in the PubMed database; a second search was carried out using the Google Scholar search engine; and a third, manual search was conducted from the articles selected through the electronic search. The keywords used for this search were extracted and developed from the titles and the MEDLINE thesaurus. The computerized search strategy was based on the following Boolean equations, classified according to four concepts (**Table 1**).

The keywords used were: cyclic fatigue, EDTA, nickel-titanium, sodium hypochlorite, surfactant, lubricant, corrosion, surface defects, instrument fracture and microcracks. PubMed was retained as an exhaustive, open-access database of the biomedical and life-science literature indexed in MEDLINE, and Google Scholar as a complementary engine indexing academic publications, theses and citations beyond MEDLINE coverage. The manual search consisted of a bottom-up screening of the bibliographic references of the articles retained by the electronic search. On PubMed, the final search equation, combining the four concepts of **Table 1**, was as follows: ("nickel-titanium" [tiab] OR "NiTi" [tiab]) AND ("cyclic fatigue" [tiab] OR "corrosion"[tiab] OR "surface defects" [tiab] OR "microcracks" [tiab]

OR "instrumental fracture" [tiab]) AND ("EDTA" [tiab] OR "sodium hypochlorite" [tiab] OR "surfactant" [tiab] OR "lubricant" [tiab]), with date (2006-2023) and language (English, French) filters applied directly in the PubMed interface. On Google Scholar, which does not allow advanced Boolean filtering, a simplified equation combining the main descriptors ("nickel-titanium" AND "cyclic fatigue" OR "corrosion" AND "EDTA" OR "sodium hypochlorite") was used, and the results were sorted by relevance and then screened by title until the apparent relevance of the results was exhausted. Both searches were conducted during 2023, the period covered by our inclusion criteria.

Table 1. Classification of the Boolean equations.

Concept 1: Cyclic fatigue	Cyclic fatigue AND EDTA OR Sodium hypochlorite, Nickel-titanium AND Corrosion AND EDTA OR Sodium hypochlorite
Concept 2: Corrosion	Nickel-titanium AND Corrosion, Nickel-titanium AND Microcracks or Surface defects OR Instrumental fracture
Concept 3: Surface topography	Surface defects AND EDTA, Microcracks AND Surfactant OR Lubricant; Instrumental fracture AND EDTA OR Sodium hypochlorite
Concept 4: Nickel-titanium	Nickel-titanium AND EDTA OR Sodium hypochlorite, Nickel-titanium AND Lubricant OR Surfactant

The articles selected in our search include all literature reviews, systematic reviews, meta-analyses and laboratory (*in vitro*) studies meeting the following inclusion criteria: articles meeting the objectives of our research on the behavior of files in response to chelating agents and irrigants, articles published in English or French, and articles published between 2006 and 2023. The articles excluded from our computerized search were the following: articles not meeting the objectives of our study; articles published before 2006; and articles published in a language other than English or French. We identified 302 PubMed references using search queries incorporating filters based on our inclusion and exclusion criteria. We obtained 220 references from Google Scholar using search queries incorporating filters based on our inclusion and exclusion criteria. This step was carried out using the Zotero software. A total of 196 duplicates were counted. The manual search did not identify any additional eligible article. The initial selection of articles was based on the title, making it possible to determine whether or not they met the research objectives. A second selection was then carried out on the basis of reading the abstract. Finally, a third, full-text reading of the selected articles was carried out, eliminating those that did not meet the inclusion criteria listed above. Finally, the database analyzed in the Results and Discussion sections is represented by the number of articles selected. The flow diagram below summarizes the article screening steps, from the initial corpus (522 articles) to the final corpus (30 articles) (See **Figure 1**).

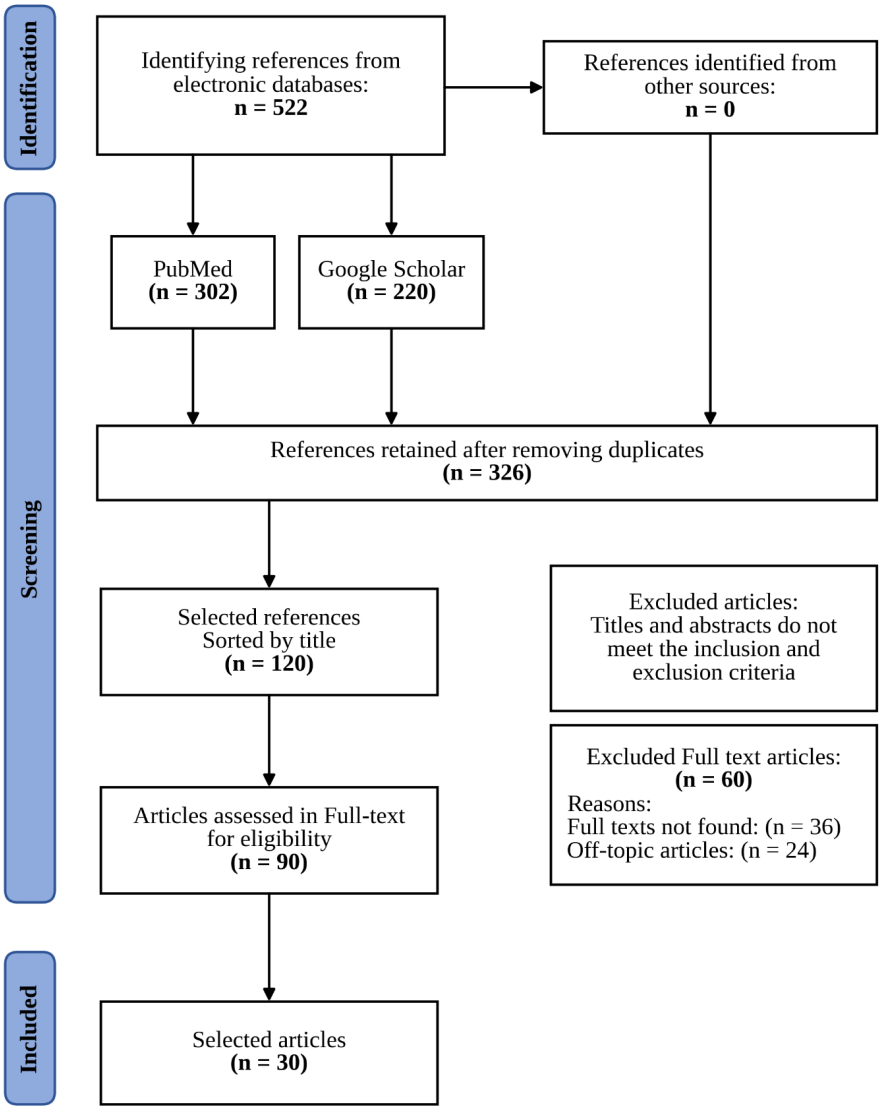


Figure 1. Flow diagram of the article search and selection process according to the PRISMA 2020 criteria.

3. Results

3.1. Selection and Definition of the Included Studies

The search of the PubMed and Google Scholar databases, using various combinations of keywords, identified 522 records (302 from PubMed and 220 from Google Scholar). After removal of 196 duplicates, 326 records remained. Screening of titles excluded 206 records, leaving 120 records. A second screening step, based on the reading of the abstracts, excluded a further 30 records that did not meet the inclusion and exclusion criteria, leaving 90 articles to be assessed in full text. The in-depth critical analysis of these 90 full texts resulted in the final inclusion of 30 articles, 60 articles being excluded at this stage for the following reasons: full text not found or unavailable (n = 36) and off-topic articles not meeting the objectives of the study (n = 24) (Figure 1). The 30 included articles were retained because of

their relevance to our field of research; their methodological quality is assessed in section 3.2. In accordance with our eligibility criteria restricted to publications in English or French, almost all of the included articles were published in English. To clearly identify the selected studies, we classified them by author, title, country and year of publication (see section 3.3).

3.2. Assessment of Methodological Quality

The methodological quality of the 30 included studies was assessed using an abridged version of the QUIN tool (Quality Assessment Tool for *in Vitro* Studies in Dentistry), covering four criteria that can be verified directly from the data already extracted for the summary of the articles (section 3.5): the presence of an explicit control or comparator group, the mention of randomization when allocating samples, the reporting of the sample size, and the mention of a statistical analysis. Studies meeting all four criteria were classified as "High", those meeting two or three as "Moderate" and those meeting fewer than two as "Low". The results of this assessment are presented in Table 2.

Table 2. Simplified QUIN assessment of the 30 included studies.

No.	Author (study)	Control/ comparator	Randomi-zation	Sample size	Statistical analysis	Quality level
1	Pedullà *et al*. 2014	Yes	Not specified	Yes (n = 270)	Not specified	Moderate
2	Pedullà *et al*. 2013	Yes	Yes	Yes (n = 90)	Not specified	Moderate
3	Orozco-Ocampo *et al*. 2022 (scoping review)	Not specified	Not specified	Not specified	Not specified	Low
4	Jose *et al*. 2021	Not specified	Not specified	Not specified	Not specified	Low
5	Keles *et al*. 2019	Yes (distilled water)	Not specified	Not specified	Not specified	Low
6	Ertuğrul 2019	Yes (distilled water)	Not specified	Not specified	Not specified	Low
7	Sonntag & Peters 2007	Yes	Not specified	Yes (n = 140)	Not specified	Moderate
8	Uslu *et al*. 2018	Yes	Yes	Yes (n = 200)	Not specified	Moderate
9	Alfawaz *et al*. 2018 (ProTaper Gold)	Yes (distilled water)	Not specified	Yes (n = 135)	Not specified	Moderate
10	Hamdy *et al*. 2023	No (before/after)	Not specified	Yes (n = 50)	Yes (t-test, ANOVA)	Moderate
11	Alfawaz *et al*. 2022 (ETP/PTG)	Yes	Yes	Yes (n = 120)	Yes (LSD)	High
12	Erik & Özyürek 2019	Yes (distilled water)	Yes	Yes (n = 300)	Not specified	Moderate
13	Bonaccorso *et al*. 2008	Yes	Not specified	Yes (n = 30)	Not specified	Moderate

Continued

14	Pallewar *et al*. 2019	Yes	Not specified	Yes (n = 81)	Yes (ANOVA)	Moderate
15	Prasad *et al*. 2014	Yes	Not specified	No (n = 8)	Yes (t-test, ANOVA)	Moderate
16	Ametrano *et al*. 2011	Yes	Not specified	Yes (n = 20)	Yes (ANOVA, t-test)	Moderate
17	Hasegawa *et al*. 2014	Yes (distilled water)	Not specified	No (n = 3)	Not specified	Low
18	Dagna *et al*. 2014	Yes	Not specified	Yes (n = 135)	Not specified	Moderate
19	Oktavia *et al*. 2019	No (comparative)	Not specified	Yes (n = 24 teeth)	Not specified	Low
20	Cheung & Darvell 2008	Not specified	Not specified	Yes (n = 179)	Not specified	Low
21	Elnaghy & Elsaka 2017	Yes	Yes	Yes (n = 180)	Not specified	Moderate
22	Berutti *et al*. 2006	Yes	Not specified	Yes (n = 120)	Not specified	Moderate
23	Topçuoğlu *et al*. 2016	Yes	Yes	Yes (n = 90)	Not specified	Moderate
24	Pedullà *et al*. 2011	Yes	Yes	Yes (n = 150)	Not specified	Moderate
25	Cai *et al*. 2017	Yes	Not specified	Yes (n = 72)	Yes (ANOVA)	Moderate
26	Bulem *et al*. 2013	Yes	Not specified	Yes (n = 160)	Not specified	Moderate
27	Topuz *et al*. 2008	Yes	Not specified	No (n = 4)	Not specified	Low
28	Sağlam *et al*. 2012	Yes	Not specified	No (n = 4)	Not specified	Low
29	De Castro Martins *et al*. 2006	Yes	Yes	Yes (n = 80)	Not specified	Moderate
30	Javadi *et al*. 2023	Yes	Yes	Yes (n = 90)	Yes (ANOVA, LSD)	High

This assessment was performed by a single evaluator from the data already synthesized in the summary of the articles (section 3.5), rather than by an independent re-reading of the full text of each of the 30 articles. Criteria rated "Not specified" reflect the absence of this information in our synthesis and do not prejudge its presence in the source publication, so that the randomization and statistical-analysis criteria are probably under-reported. This single-evaluator appraisal, based on the extracted data rather than on the full texts, is therefore indicative only and is acknowledged among the limitations of this review.

Based on this, 9 of the 30 studies (30%) explicitly report randomization when constituting the groups, whereas this point is not specified in the available extraction for the other 21; only seven studies (nos. 10, 11, 14, 15, 16, 25 and 30) explicitly mention a statistical test (analysis of variance). A control or comparator group is identifiable in 25 of the 30 studies. According to these four criteria, two studies (nos. 11 and 30) were classified as "High", 19 as "Moderate" and 9 as "Low"; the

other studies mostly lack information on randomization, justified sample size and statistical analysis in the available data. This distribution should be interpreted with caution: it reflects the limits of our extraction as much as the actual quality of the source studies. In the Discussion, conclusions drawn mainly from studies with a small sample size (nos. 15, 17, 27 and 28) or classified as "Low" should be flagged as less robust.

3.3. Description of the Characteristics of the Included Studies

The main characteristics of the 30 studies included in this review are listed in Table 3, which identifies each study by its number, first author(s), full title, country of origin and year of publication. The studies were published between 2006 and 2023: nine between 2006 and 2012, eleven between 2013 and 2018 and ten between 2019 and 2023, which shows that the question of the effect of irrigants on NiTi instruments has remained a continuous research topic over the last two decades. They were conducted in twelve different countries, with Turkey (8 studies) and Italy (7 studies) contributing the largest share, followed by India (3 studies); the geographical distribution is detailed in Table 4. The titles show that most of the studies investigated the cyclic fatigue resistance of NiTi files after immersion in sodium hypochlorite and/or EDTA, whereas the others focused on surface topography and roughness (notably by atomic force microscopy) or on corrosion behavior.

Table 3. Summary of the selected articles.

No.	Author	Title	Country	Year
1	Pedullà *et al.*	Cyclic Fatigue Resistance of Nickel-Titanium Instruments after Immersion in Irrigant Solutions with or without Surfactants	Italy	2014
2	Pedullà *et al.*	Cyclic Fatigue Resistance of Two Reciprocating Nickel-Titanium Instruments After Immersion in Sodium Hypochlorite	Italy	2013
3	Orozco-Ocampo *et al.*	Fatigue Failure of NiTi Endodontic Files	Colombia	2022
4	Jose *et al.*	Qualitative Assessment of the Surface Topographic Changes of XP-endo Shaper and TruNatomy Files After Exposure to Sodium Hypochlorite and Ethylenediaminetetraacetic Acid	India	2021
5	Keles *et al.*	Effect of Sodium Hypochlorite on Cyclic Fatigue Resistance of Heat-Treated Reciprocating Files	Turkey	2019
6	Ertuğrul İ	Effect of NaOCl Solution on the Cyclic Fatigue Resistance of Traditional and Heat-Treated File Systems	Turkey	2019
7	Sonntag & Peters	Effect of Prion Decontamination Protocols on Nickel-Titanium Rotary Surfaces	Germany	2007
8	Uslu *et al.*	Effect of Dynamic Immersion in Sodium Hypochlorite and EDTA Solutions on Cyclic Fatigue Resistance of WaveOne and WaveOne Gold Reciprocating Nickel-Titanium Files	Turkey	2018

Continued

9	Alfawaz *et al*.	Effects of Sodium Hypochlorite Concentration and Temperature on the Cyclic Fatigue Resistance of Heat-Treated Nickel-Titanium Rotary Instruments	Saudi Arabia	2018
10	Hamdy *et al*.	Impact of Endodontic Irrigants on the Surface Roughness of Various Nickel-Titanium Rotary Endodontic Instruments	Egypt	2023
11	Alfawaz *et al*.	Effect of NaOCl and EDTA Irrigating Solutions on the cyclic fatigue resistance of EdgeTaper Platinum instruments	Saudi Arabia	2022
12	Erik & Özyürek	Effects of etidronate, NaOCl, EDTA irrigation solutions and their combinations on the cyclic fatigue resistance of nickel-titanium single-file rotary and reciprocating instruments at body temperature	Turkey	2019
13	Bonaccorso *et al*.	Pitting Corrosion Resistance of Nickel-Titanium Rotary Instruments with Different Surface Treatments in 17 Percent Ethylenediaminetetraacetic Acid and Sodium Chloride Solutions	Italy	2008
14	Pallewar *et al*.	Effect of NaOCl and EDTA Solutions on the Topography of ESX, TruShape and ProTaper Gold NiTi Rotary Instruments - An Atomic Force Microscopy Study	India	2019
15	Prasad *et al*.	The Effect of 5% Sodium Hypochlorite, 17% EDTA, and Triphala on Two Different Rotary Ni-Ti Instruments: An AFM and EDS Analysis	India	2014
16	Ametrano *et al*.	Effects of sodium hypochlorite and ethylenediaminetetraacetic acid on rotary nickel-titanium instruments evaluated using atomic force microscopy	Italy	2011
17	Hasegawa *et al*.	Effect of EDTA Solution on Corrosion Fatigue of Ni-Ti Files with Different Shapes	Japan	2014
18	Dagna *et al*.	Cyclic Fatigue Resistance of Three Niti Single-File Systems after Immersion in EDTA	Italy	2014
19	Oktavia *et al*.	Effect of Sodium Hypochlorite, EDTA, and Chitosan Solution on Corrosion and Quantity of Extruded Nickel Ions Using Two Rotary Instruments (*In Vitro*)	Indonesia	2019
20	Cheung & Darvell	Low-cycle fatigue of rotary NiTi endodontic instruments in hypochlorite solution	China	2008
21	Elnaghy & Elsaka	Effect of sodium hypochlorite and saline on the cyclic fatigue resistance of WaveOne Gold and Reciproc reciprocating instruments	Egypt	2017
22	Berutti *et al*.	Influence of Sodium Hypochlorite on the Fracture Properties and Corrosion of ProTaper Rotary Instruments	Italy	2006
23	Topçuoğlu *et al*.	Cyclic Fatigue Resistance of D-RaCe, ProTaper, and Mtwo Nickel-Titanium Retreatment Instruments After Immersion in Sodium Hypochlorite	Turkey	2016

Continued

24	Pedullà *et al*.	Cyclic Fatigue Resistance of Three Different Nickel-Titanium Instruments After Immersion in Sodium Hypochlorite	Italy	2011
25	Cai *et al*.	Effect of Irrigation on Surface Roughness and Fatigue Resistance of Controlled Memory Wire Nickel-Titanium Instruments	China	2017
26	Bulem *et al*.	Experimental evaluation of cyclic fatigue resistance of four different nickel-titanium instruments after immersion in sodium hypochlorite and/or sterilization	Turkey	2013
27	Topuz *et al*.	Structural effects of sodium hypochlorite solution on RaCe rotary nickel-titanium instruments: an atomic force microscopy study	Turkey	2008
28	Sağlam *et al*.	Effects of Irrigation Solutions on the Surface of ProTaper Instruments: A Microscopy Study	Turkey	2012
29	De Castro Martins *et al*.	The Effect of Sodium Hypochlorite on the Surface Characteristics and Fatigue Resistance of ProFile Nickel-Titanium Instruments	Brazil	2006
30	Javadi *et al*.	Effect of Immersion in Disinfectants on the Cyclic Fatigue Resistance of Nickel-Titanium Instruments: An *in Vitro* Study	Iran	2023

3.4. Analysis of the Data Extracted from the Selected Studies

Most of the articles came from English-language journals. Table 4 presents the different countries in which the studies were conducted.

Table 4. Number of studies by country.

Continent	Country	Number of studies
Africa	Egypt	2
Americas	Brazil	1
	Colombia	1
Asia	Türkiye	8
	Saudi Arabia	2
	Japan	1
	India	3
	China	2
	Indonesia	1
	Iran	1
Europe	Germany	1
	Italy	7

3.5. Summaries of the Selected Studies

The summary of the articles is presented in the form of comprehensive summary tables (Table 5), which identify the objectives and characteristics of each study, as well as the results and conclusions, according to the PECO criteria.

Table 5. Summary of the selected articles according to the PECO criteria.

No.	Population	Exposure	Comparison	Result
1	Nickel-titanium endodontic instruments from three different brands: Reciproc R25, WaveOne Primary and ProTaper F2.	The instruments of each brand were divided into 5 groups: −1 control group (n = 10): unused files −4 test groups (n = 20): files dynamically immersed under the following conditions: Temperature: 37˚C Solutions: sodium hypochlorite (NaOCl) 5.25% Hypoclean (5.25% NaOCl with surfactant) 17% EDTA EDTA Plus (17% EDTA with surfactant) Duration: 45 seconds or 3 minutes	Comparison between instruments immersed in a NaOCl solution and instruments immersed in a NaOCl solution with surfactants.	Immersion in EDTA reduced the cyclic fatigue resistance of all instruments after 3 minutes. The addition of surfactants did not affect the cyclic fatigue of the files, except when they were added to NaOCl.
2	90 new files: 45 Reciproc R25 and 45 WaveOne Primary.	Random allocation of the files of each brand into 3 groups (n = 15): - Group 1: no immersion - Group 2: dynamic immersion for 1 minute in 5% NaOCl at 37˚C - Group 3: dynamic immersion for 5 minutes in 5% NaOCl at 37˚C.	Cyclic fatigue resistance of instruments immersed in a NaOCl solution for different durations, compared with that of instruments immersed in water (control group).	Reciproc R25 instruments show higher cyclic fatigue resistance than WaveOne Primary instruments. Alternating dynamic immersion in NaOCl for 1 or 5 minutes did not significantly reduce the cyclic fatigue resistance of the NiTi files.
3	Nickel-titanium endodontic instruments.	Exposure of nickel-titanium (NiTi) endodontic instruments to specific endodontic procedure conditions, simulating the stresses encountered in clinical practice.	Comparison of the fatigue rates of nickel-titanium files in contact with EDTA and NaOCl.	Immersion in sodium hypochlorite does not affect fatigue resistance. However, immersion in EDTA for more than three minutes significantly affects fatigue resistance.
4	Endodontic instruments of the following types: XP-endo Shaper and TruNatomy, used during endodontic procedures.	Exposure of XP-endo Shaper and TruNatomy instruments to a NaOCl and EDTA solution according to standard endodontic protocols.	Comparison of the effects of two irrigating agents, NaOCl and EDTA, on XP-endo Shaper and TruNatomy endodontic instruments.	Surface roughness was lower for XP-endo Shaper compared with TruNatomy. A 17% EDTA concentration resulted in significantly higher surface roughness for both file systems compared with a 5.25% NaOCl concentration.

Continued

5	Reciprocating endodontic instruments that had previously undergone heat treatment.	Exposure of heat-treated reciprocating files to NaOCl solutions at different temperatures.	Comparison of the effects of different NaOCl temperatures on the cyclic fatigue resistance of heat-treated files. (Reciproc Blue, Reciproc 25, Wave One Primary, Wave One Gold Primary and One Shape).	Immersion in NaOCl at 60˚C had drastic effects on the cyclic fatigue life of the instruments. Reciproc Blue showed higher cyclic fatigue resistance than the other systems. Heat-treated instruments demonstrated better cyclic fatigue resistance than traditional NiTi instruments.
6	ProTaper Gold F2 and ProTaper Universal F2 endodontic instruments	The files were immersed in distilled water and in NaOCl for 5 minutes, then rotated in an artificial canal with a curvature angle of 60˚ and a radius of curvature of 5 mm.	To compare the cyclic fatigue resistance of ProTaper Gold and ProTaper Universal instruments immersed in distilled water and in 5.25% NaOCl solution, respectively.	ProTaper Gold files show higher cyclic fatigue resistance than ProTaper Universal files. ProTaper Universal files immersed in distilled water showed higher cyclic fatigue resistance than when they were immersed in a NaOCl solution. The ProTaper Gold system is more resistant to cyclic fatigue than the ProTaper Universal system.
7	7 brands of NiTi files: -AlphaFile -FlexMaster -K3 -MTwo -ProFile -ProTaper 34 - RaCE.	The instruments were divided into 4 groups of 35 instruments each (5 of each type of file per group) and subjected to different decontamination solutions. -Group 1 (NaOH): 2M sodium hydroxide (pH 13.8) -Group 2 (NaOCl): 3% sodium hypochlorite (pH 12.3) -Group 3 (CH_5N_3): 6M guanidine thiocyanate (pH 6) -Group 4 (control): air-drying after immersion in distilled water.	To compare the effect of different decontamination solutions on the corrosion of 7 different brands of files.	Immersion in NaOCl caused significant corrosion of the instruments tested. No degradation was observed with the other decontamination solutions (NaOH and CH5N3). The results show that the exclusive use of NiTi files is the best way to prevent corrosion.
8	NiTi endodontic instruments operating in reciprocating mode, specifically WaveOne and WaveOne Gold files.	Exposure of the instruments to dynamic immersion in NaOCl and EDTA solutions.	Comparison of cyclic fatigue resistance between WaveOne and WaveOne Gold files after dynamic immersion in NaOCl and EDTA solutions.	NaOCl and EDTA solutions had no effect on the cyclic fatigue resistance of WaveOne and WaveOne Gold files.

Continued

9	135 ProTaper Gold instruments.	Exposure of the files to different concentrations of NaOCl and to different temperatures (25˚C, 37˚C and 60˚C).	Comparison of cyclic fatigue resistance between ProTaper Gold files subjected to different NaOCl concentrations and different temperatures.	An increase in the ambient temperature of the NaOCl solution reduces fatigue resistance.
10	5 NiTi rotary endodontic instruments (ProTaper Next, Hyflex CM, HyflexEDM, WaveOne and TruNatomy).	The files were subjected to atomic force microscopy (AFM) analysis; each file was then rotated in 5.25% NaOCl for 15 minutes, followed by a new AFM analysis.	Comparison of surface roughness between the different nickel-titanium rotary instruments after rotation in 5.25% NaOCl for 15 minutes, with speed and torque set according to the manufacturers' instructions.	TruNatomy and ProTaper Next instruments showed the lowest surface roughness. All NiTi rotary instruments tested after exposure to irrigants showed an increase in surface roughness.
11	60 ProTaper Gold instruments and 60 EdgeTaper Platinum instruments of the same size and taper (8%).	Exposure of the instruments to various irrigating solutions after allocation into 3 groups of 20 each: -Group 1: 20 PTG and 20 ETP exposed to 17% EDTA -Group 2: 20 PTG and 20 ETP exposed to 5.25% NaOCl -Group 3: 20 PTG and 20 ETP exposed to distilled water	Comparison of cyclic fatigue resistance between EdgeTaper Platinum and ProTaper Gold instruments after exposure to various irrigating solutions, namely NaOCl, EDTA and distilled water	EdgeTaper demonstrated improved cyclic fatigue performance compared with ProTaper Gold in all irrigating solutions tested. EDTA can be used in combination with NiTi instruments during canal preparation without compromising the cyclic fatigue resistance of PTG and ETP instruments. However, NaOCl drastically decreased the number of cycles to fracture of both systems.
12	100 WaveOne Gold, 100 NiTi Reciproc Blue and 100 HyFlex EDM NiTi.	Random allocation into 5 groups and immersion in the following solutions: - -Group 1: distilled water -Group 2: 6% NaOCl -Group 3: 17% EDTA -Group 4: 18% HEBP -Group 5: 6% NaOCl and 18% HEBP	To compare etidronic acid (HEBP), NaOCl and EDTA solutions, as well as their combinations, regarding their effect on the cyclic fatigue resistance of NiTi files: RPC Blue (RPC Blue), HyFlex EDM (HEDM) and WaveOne Gold (WOG).	EDTA, NaOCl and HEBP solutions did not affect cyclic fatigue resistance when used alone. The combination of NaOCl and HEBP solutions reduced cyclic fatigue resistance.

Continued

13	Electropolished and non-electropolished RaCe instruments, and Alpha instruments coated by physical vapor deposition (PVD).	Exposure of nickel-titanium rotary instruments to 17% EDTA and sodium chloride (NaCl) solutions.	Comparison of corrosion resistance between nickel-titanium rotary instruments with different surface treatments in 17% EDTA and NaCl solutions.	Risk of corrosion for NiTi instruments without surface treatment in contact with NaCl. NiTi files with PVD and electropolishing surface treatments showed increased corrosion resistance.
14	27 NiTi endodontic files of each brand: ESX, TruShape and ProTaper Gold.	Allocation of the files into 3 subgroups (n = 9): - Group 1: no immersion - Group 2: immersion in 5.25% NaOCl for 5 minutes - Group 3: immersion in 17% EDTA for 5 minutes. The file surfaces were then analyzed by atomic force microscopy (AFM).	Comparison of the effects on surface topography between ESX, TruShape and ProTaper Gold instruments after exposure to NaOCl and EDTA solutions.	A short contact time (5 min) with 5.25% NaOCl and 17% EDTA solutions caused changes in the topography of the NiTi instruments by increasing the RMS and Ra values, thereby altering the nanostructure of the instrument and making it more susceptible to corrosion.
15	8 Ni-Ti rotary files: 4 ProTaper-S2 4 iRaCe - R3	Exposure of nickel-titanium rotary instruments to 5% sodium hypochlorite, 17% ethylenediaminetetraacetic acid (EDTA) and triphala solutions for 5 min.	Comparison of the effects of 5% sodium hypochlorite, 17% EDTA and triphala solutions on Ra, RMS and Rc.	Short-term exposure (5 min) to 17% EDTA and 5% NaOCl can cause surface deterioration of ProTaper and iRaCe NiTi rotary files. iRaCe files immersed in sodium hypochlorite and EDTA showed significantly higher surface roughness values than those immersed in Triphala. This difference could be explained by the less reactive nature of Triphala, a hydrocarbon-based compound, compared with the other irrigating solutions examined.
16	20 ProTaper instruments (Dentsply Maillefer, Ballaigues, Switzerland) (S1, S2, F1, F2).	Allocation of the files into 5 groups: -Group 1: no immersion -Group 2: immersion in 5.25% NaOCl for 5 minutes. -Group 3: immersion in 5.25% NaOCl for 10 minutes. -Group 4: immersion in 17% EDTA for 5 minutes - Group 5: immersion in 17% EDTA for 10 minutes Followed by analysis of the results by AFM.	Comparison of the effects of NaOCl and EDTA on ProTaper nickel-titanium rotary instruments.	Immersion in 5.25% NaOCl and 17% EDTA altered the surface roughness of the ProTaper files by increasing the RMS and Ra values, thus causing surface degradation. Roughness values were higher after immersion in 5.25% NaOCl for 10 minutes.

Continued

17	3 Ni-Ti instruments of different shapes: Flex Master, RaCe and K3.	The files were subjected to rotating bending in a curved glass tube (at angles of 30˚ and 60˚) filled with one of the following solutions: −3% EDTA −10% EDTA −6% NaOCl −3% H_2O_2 - 0.9% NaCl -Distilled water	Comparison of corrosion and fatigue levels between nickel-titanium files of different shapes exposed to an EDTA solution and to other solutions at different angles.	Bending angle 30˚: all files in the five solutions 3% and 10% EDTA, 6% NaOCl, 3% H_2O_2 and 0.9% NaCl show significantly lower fatigue resistance than files immersed in distilled water. The above solutions reduce the fatigue resistance of the files tested. EDTA-based solutions have a more marked negative effect on fatigue resistance. Bending angle 60˚: early failure (1 to 2.5 minutes) for all files in all solutions, with no significant difference. Limitation of file use to a few minutes in severely curved canals.
18	135 new NiTi endodontic instruments, divided into three groups of 45: OneShape, Reciproc R25 and WaveOne Primary.	The three systems were subjected to different immersion protocols: −1 minute in 10% EDTA at 37˚C −5 minutes in 10% EDTA at 37˚C -no immersion A cyclic fatigue test was then performed in an artificial stainless steel canal curved at an angle of 60˚ with a radius of curvature of 5 mm.	To compare the *in vitro* cyclic fatigue resistance of three single-use NiTi endodontic instrument systems (OneShape, Reciproc and WaveOne) after immersion in a 10% EDTA solution for varying durations.	Immersion in EDTA for 1 or 5 minutes did not reduce the cyclic fatigue resistance of the NiTi systems. The number of cycles to failure (NCF) for Reciproc R25 was higher than that of OneShape and WaveOne Primary. The OneShape systems demonstrated promising mechanical strength, similar to that of WaveOne Primary.
19	Twenty-four extracted human premolars. - NiTi files: ProTaper Universal and iRace.	The twenty-four extracted human premolars were divided into 4 groups: Group 1: instrumentation with ProTaper Universal, irrigation with 2.5% NaOCl and 17% EDTA. Group 2: instrumentation with ProTaper Universal, irrigation with 2.5% NaOCl and 0.2% chitosan solution. - Group 3: instrumentation with iRace, irrigation with 2.5% NaOCl and 17% EDTA. Group 4: instrumentation with iRace, irrigation with 2.5% NaOCl and 0.2% chitosan solution.	To compare the effect of 2.5% NaOCl, 17% EDTA and a 0.2% high-molecular-weight chitosan solution during canal preparation with ProTaper Universal and iRace on the corrosion of NiTi instruments.	The combination of 2.5% NaOCl and 0.2% high-molecular-weight chitosan solution reduced corrosion and surface defects on ProTaper Universal and iRace files, compared with a combination of 2.5% NaOCl and 17% EDTA. The 0.2% molecular chitosan solution could be developed as a chelating agent (an alternative to EDTA).

Continued

20	179 NiTi instruments of 4 different brands: ProFile, K3, HERO Shaper and FlexMaster.	The 4 brands of NiTi rotary instruments were tested for their resistance to fracture under rotating-bending fatigue using a custom-built machine, which flexed the instrument after immersion in NaOCl.	To compare the rotating-bending fatigue resistance of 4 brands of NiTi rotary instruments immersed in a 1.2% NaOCl solution.	The rotating-bending fatigue resistance of NiTi rotary instruments is brand-dependent and is influenced by NaOCl, which corrodes NiTi instruments by creating microcracks on their surface.
21	180 new NiTi instruments: 90 WaveOne Gold and 90 Reciproc.	Random allocation of the files into 3 groups: -Group 1: no immersion -Group 2: immersion in saline solution at 37˚C. -Group 3: immersion in 5% NaOCl at 37˚C. The instruments were then subjected to reciprocating motion in the test solution until failure, and the number of cycles to failure was recorded.	To compare the cyclic fatigue resistance of WaveOne Gold and Reciproc reciprocating instruments during immersion in sodium hypochlorite (NaOCl) and saline solutions.	Immersion of WaveOne Gold and Reciproc instruments in saline and NaOCl solutions reduced their cyclic fatigue resistance. The fatigue resistance of WaveOne Gold instruments was higher than that of Reciproc instruments.
22	120 ProTaper NiTi files (F2).	The files were divided into 3 groups: -Group 1 (control): non-immersed files -Group 2: files immersed to 20 mm in 5% NaOCl at 50˚C for 5 minutes - Group 3: files fully immersed in 5% NaOCl at 50˚C for 5 minutes	Evaluation of the effect of immersion in NaOCl on ProTaper rotary instruments.	The results showed that Group 3 has significantly lower cyclic fatigue resistance than Groups 1 and 2. The presence of several metals in the ProTaper instruments tested, interacting with the properties of NaOCl, led to galvanic reactions and subsequent corrosion.
23	90 canal retreatment instruments: ProTaper, D-RaCe and Mtwo.	The instruments were randomly divided into two groups (n = 15): Group 1: non-immersed (control group) Group 2: immersed in 5% NaOCl at 37˚C for 5 minutes. All instruments were then subjected to a cyclic fatigue test.	Comparison of the effect of immersion in sodium hypochlorite (NaOCl) on the cyclic fatigue resistance of three nickel-titanium retreatment rotary instruments.	D-RaCe retreatment instruments showed the highest cyclic fatigue resistance among the other retreatment instruments tested in this study. Immersion in NaOCl reduced the cyclic fatigue resistance of the D-RaCe retreatment instrument.

Continued

24	150 new files: 50 Twisted Files, 50 Revo S SU and 50 Mtwo.	The files were randomly divided into five groups (n = 10) for each type of file: - Group 1: no immersion - Group 2: static immersion for 5 minutes -Group 3: static immersion for 1 minute - Group 4: dynamic immersion (300 rpm) for 5 minutes - Group 5: dynamic immersion (300 rpm) for 1 minute Cyclic fatigue resistance was determined by counting the number of cycles to failure in a simulated root canal with a curvature angle of 60˚ and a radius of curvature of 5 mm.	To compare the cyclic fatigue resistance of three nickel-titanium (NiTi) instruments after immersion in a sodium hypochlorite (NaOCl) solution under conditions close to clinical practice.	Static or dynamic immersion in NaOCl for 1 or 5 minutes did not reduce the cyclic fatigue resistance of the NiTi instruments. The type of instrument influences cyclic fatigue resistance. Twisted Files showed the highest resistance, followed by Mtwo and then Revo S SU.
25	HyFlex and M3 controlled-memory nickel-titanium instruments.	36 files of each brand were divided into three groups: Group 1: new files; Group 2: files immersed in 5.25% NaOCl Group 3: files immersed in 17% EDTA The files were rotated until fracture. The number of rotations to fracture was compared between the groups using analysis of variance (ANOVA).	To compare the effect of irrigation on the surface roughness and fatigue resistance of CM-coated nickel-titanium HyFlex and M3 instruments.	The surface roughness of M3 instruments exposed to irrigants increased compared with HyFlex instruments immersed in NaOCl. A change in the surface topography of the instruments caused by 10 minutes of contact with the irrigants did not lead to a decrease in cyclic fatigue resistance.
26	160 NiTi files: 40 ProFile, 40 FlexMaster, 40 Mtwo and 40 TwistedFiles.	The 40 instruments were divided into four subgroups (n = 10) for each type of file: - Group 1: immersion in 2.5% NaOCl for 5 minutes -Group 2: immersion in NaOCl + autoclave sterilization (1 cycle) -Group 3: 5 immersion/sterilization cycles -Control group: no immersion or sterilization	To compare the effects of immersion in NaOCl and autoclave sterilization on the cyclic fatigue resistance of ProFile, FlexMaster, Mtwo and Twisted Files instruments.	The cyclic fatigue resistance of the NiTi instruments tested was not negatively affected by immersion in NaOCl or by autoclave sterilization. The manufacturing process (TwistedFiles) or the design of the instruments (Twisted Files, FlexMaster, Mtwo and ProFile) could positively influence their cyclic fatigue resistance.

Continued

27	4 RaCe NiTi rotary files.	Classification of the files into 2 groups: Group 1 (NaOCl immersion): one 30.06 file and one 30.02 file were immersed in a 5.25% NaOCl solution for 5 minutes. Group 2 (Control): one 30.06 file and one 30.02 file were kept as controls without immersion in NaOCl.	To compare the effect of immersion in NaOCl on the surface characteristics of two RaCe nickel-titanium rotary instruments using atomic force microscopy (AFM).	NaOCl causes surface degradation of RaCe instruments.
28	4 new ProTaper F3 NiTi rotary files.	Immersion of 4 NiTi files in 4 different irrigating solutions: 2.5% NaOCl, 5% NaOCl, 2% CHX and MTAD for 10 min.	Comparison of the effects of sodium hypochlorite (NaOCl), chlorhexidine digluconate (CHX) and a mixture of doxycycline (a tetracycline isomer), citric acid and detergent (MTAD) on the surfaces of nickel-titanium rotary files.	The 2.5% NaOCl, 5% NaOCl and MTAD irrigating solutions caused surface alterations on ProTaper NiTi files.
29	80 new ProFile instruments.	The 80 files were divided into 4 groups: one control group and three experimental groups; these were immersed in a 5.25% NaOCl solution for 24 hours and then used to shape curved root canals.	Comparison of the effect of 5.25% NaOCl on the surface characteristics and fatigue resistance of ProFile.	Immersion in 5.25% NaOCl for 24 hours had no effect on the surface characteristics and fatigue resistance.
30	90 M3 Pro Gold and SP1 (VTaper Gold) NiTi files.	The files were randomly divided into 3 groups (n = 15) for each type of file. The immersion protocol (5 minutes at room temperature) was as follows: Control group: no immersion Group 1: immersion in 5% NaOCl Group 2: immersion in Deconex	To compare the cyclic fatigue resistance of two NiTi rotary files after immersion in 5% NaOCl and Deconex.	The cyclic fatigue resistance of the control-group M3 files is higher than that of the files immersed in Deconex and NaOCl. The cyclic fatigue resistance of M3 and SP1 files immersed in Deconex is higher than that of the files immersed in NaOCl. NaOCl reduced the cyclic fatigue resistance of M3 Pro Gold files, whereas immersion in Deconex increased the cyclic fatigue resistance of SP1 files.

4. Discussion

Before presenting these results, it should be emphasized that the effect of irrigating

solutions on NiTi instruments is not uniform: it is strongly modulated by effect modifiers such as the alloy and heat treatment of the instrument (conventional NiTi, CM wire, or heat-treated instruments), the kinematics used (continuous rotation versus reciprocating motion), the geometry and curvature of the simulated canal, the concentration of the irrigant, the duration of exposure and the temperature of the solution. These parameters vary considerably from one included study to another, and the conclusions summarized below should therefore be interpreted as conditioned by this experimental heterogeneity rather than as universal effects.

Our discussion will be organized in three parts:

The first part will compare cyclic fatigue resistance during immersion in EDTA and NaOCl according to three parameters: immersion time, temperature and concentration.

In the second part, we will compare and discuss the effect of irrigating solutions on the topography of nickel-titanium instruments. Finally, the third part will compare the effects of endodontic irrigants on the corrosion of NiTi files.

4.1. Strengths and Limitations of This Study

This systematic literature review examined the effect of several endodontic irrigants, notably EDTA and NaOCl, on nickel-titanium instruments. Our literature search covered articles published in French and English between 2006 and 2023. Our aim was to review recent articles and to select studies conducted in significantly advanced scientific settings that could have a positive impact on the validity of our results. The searches were carried out in the PubMed and Google Scholar databases, restricted to articles published in English or French, in order to identify relevant reports. Unlike reviews restricted to cyclic fatigue, this review brings together studies on the cyclic fatigue, surface topography and corrosion of nickel-titanium instruments exposed to NaOCl, EDTA and other canal irrigants. The limitations of this review are discussed in the Conclusion.

4.2. Comparison of Cyclic Fatigue Resistance during Immersion in EDTA and/or NaOCl

4.2.1. Cyclic Fatigue Resistance According to Immersion Time

The study of the effect of irrigants on the cyclic fatigue of endodontic files is crucial, because irrigants such as NaOCl and EDTA are commonly used to clean and disinfect root canals during endodontic preparation procedures. Cyclic fatigue occurs when nickel-titanium rotary instruments are subjected to repeated cycles of bending and rotation, which can lead to their premature failure. Studies such as the one conducted by Pedullà *et al.* in 2014 evaluated the cyclic fatigue resistance of nickel-titanium files operating in reciprocating motion (Reciproc and WaveOne) and in continuous rotation (ProTaper) after immersion in various irrigating solutions, with or without surfactants, for several short periods [1].

Using a total of 270 Reciproc R25, Wave One Primary and ProTaper F2 files,

the instruments of each brand were divided into a control group (n = 10) consisting of new files and four test groups (n = 20) consisting of files dynamically immersed at 37˚C in 5.25% NaOCl, Hypoclean (5.25% NaOCl with surfactant), 17% EDTA and EDTA Plus (17% EDTA with surfactant). Each test group was subdivided into 2 subgroups (n = 10) according to the duration of dynamic immersion in the irrigant (45 seconds or 3 minutes). Cyclic fatigue resistance was determined by recording the time to failure in an artificial stainless steel canal with a curvature angle of 60˚ and a radius of curvature of 5 mm [1].

The fracture surface was examined under a scanning electron microscope. The study concluded that immersion in NaOCl did not reduce the cyclic fatigue resistance of NiTi files in reciprocating or continuous rotation, whereas EDTA reduced the fatigue resistance of all instruments after 3 minutes. In contrast, immersion in surfactant-containing irrigants did not affect the cyclic fatigue of the instruments, with the exception of Reciproc files immersed in a Hypoclean solution [1].

Consequently, immersion in EDTA reduced the cyclic fatigue resistance of all instruments after 3 minutes; the addition of surfactants did not affect the cyclic fatigue of the files, except when they were added to NaOCl [1].

In the same context, a scoping review by Orozco-Ocampo *et al*., synthesizing secondary evidence rather than new experimental data, reports that immersion in NaOCl does not affect cyclic fatigue resistance, but that immersion in EDTA for more than three minutes is associated with a significant decrease in fatigue resistance, which is consistent with the primary studies discussed above [2].

In 2011, Pedullà *et al*. concluded, after immersing NiTi files in NaOCl statically for 1 and 5 minutes and dynamically for 1 and 5 minutes, that NaOCl does not significantly reduce cyclic fatigue resistance [3].

In 2013, the same group of researchers confirmed the results of the previous study using different batches of files randomly divided into three groups, each subjected to different durations of dynamic immersion in 5% NaOCl; the dynamic immersion and cyclic fatigue tests were carried out using a specially designed endodontic motor, and cyclic fatigue resistance was determined by recording the time to failure in an artificial stainless steel canal with a curvature angle of 60˚ and a radius of curvature of 5 mm [4].

At the end of this experiment, the cyclic fatigue resistance of the NiTi files was not significantly affected by immersion in NaOCl; Reciproc R25 files were associated with higher cyclic fatigue resistance in all groups compared with WaveOne Primary, thus concluding that immersion in NaOCl for 1 or 5 minutes did not significantly modify the cyclic fatigue resistance of the NiTi files [4].

In 2014, Dagna *et al*. found, following a cyclic fatigue test on three NiTi systems, that immersion in EDTA for 1 or 5 minutes did not reduce cyclic fatigue resistance [5].

Ertuğrul demonstrated that ProTaper Gold files show higher cyclic fatigue resistance than ProTaper Universal files. When immersed in distilled water, ProTa-

per Universal files showed higher cyclic fatigue resistance than that observed after immersion in a NaOCl solution; the ProTaper Gold system is more resistant to fatigue than the ProTaper Universal system [6].

Another study by Uslu *et al*. concluded that NaOCl and EDTA solutions had no effect on the cyclic fatigue resistance of WaveOne (WO) and WaveOne Gold (WOG) files. This conclusion was reached at the end of an experiment involving 100 WO files and 100 WOG files, randomly divided into 5 groups:

- Group 1: no immersion (control)
- Group 2: immersion in 5.25% NaOCl at 37˚C ± 1˚C for 5 minutes
- Group 3: immersion in 5.25% NaOCl at 37˚C ± 1˚C for 10 minutes
- Group 4: immersion in 17% EDTA at 37˚C ± 1˚C for 5 minutes
- Group 5: immersion in 17% EDTA at 37˚C ± 1˚C for 10 minutes

The files were then used in an artificial canal until failure, and the time to failure was measured using a digital stopwatch [7].

However, a study by Elnaghy and Elsaka compared the cyclic fatigue resistance of the WaveOne Gold and Reciproc reciprocating instruments during immersion in NaOCl and saline solutions [8].

After immersing each of the above-mentioned files either in saline solution at 37˚C or in 5% NaOCl at 37˚C, the researchers found that immersion of WaveOne Gold and Reciproc instruments in saline and NaOCl solutions reduced their cyclic fatigue resistance, but that the fatigue resistance of WaveOne Gold instruments was higher than that of Reciproc instruments [8].

Another study by Topçuoğlu *et al*. concluded that D-RaCe retreatment instruments showed the highest cyclic fatigue resistance among the other retreatment instruments tested in the study, and that immersion in NaOCl reduced the cyclic fatigue resistance of D-RaCe retreatment instruments [9].

Whereas Bulem *et al*. demonstrated that the cyclic fatigue resistance of the NiTi instruments tested was not negatively affected by immersion in NaOCl or by autoclave sterilization, and that the manufacturing process or the design of the instruments could influence their cyclic fatigue resistance [10].

To compare the cyclic fatigue resistance of two NiTi rotary files after immersion in 5% NaOCl and in Deconex, a disinfectant composed of didecyldimethylammonium chloride, N-(3-aminopropyl)-N-dodecylpropane-1,3-diamine, as well as surfactants and chelating agents; Javadi *et al*. divided 90 M3 Pro Gold and SP1 NiTi files (45 of each brand) into 3 groups (n = 15 per brand), immersed for 5 minutes at room temperature:

- Control group: no immersion
- Group 1: immersion in 5% NaOCl
- Group 2: immersion in Deconex

The researchers concluded that the cyclic fatigue resistance of the control-group M3 files was higher than that of the files immersed in Deconex and NaOCl, and that the cyclic fatigue resistance of M3 and SP1 files immersed in Deconex was higher than that of the files immersed in NaOCl. Consequently, NaOCl re-

duced the cyclic fatigue resistance of M3 Pro Gold files, whereas immersion in Deconex increased the cyclic fatigue resistance of SP1 files [11].

4.2.2. Cyclic Fatigue Resistance According to Temperature

The effect of temperature on the cyclic fatigue of nickel-titanium files, in the presence of EDTA and NaOCl, is of paramount importance in dentistry. At high temperatures, EDTA can potentially alter the mechanical properties of nickel-titanium by promoting corrosion, which alters the structure of the file. In addition, hypochlorite, at high concentrations and under the effect of heat, can induce stress corrosion embrittlement, thereby aggravating cyclic fatigue.

Keles *et al*. conducted a study in 2019 to evaluate the impact of different NaOCl temperatures on the cyclic fatigue resistance of various heat-treated endodontic file systems. The systems tested were Reciproc 25, Reciproc Blue R25, WaveOne Primary, WaveOne Gold Primary and One Shape. The tests were carried out under various conditions, including immersion in distilled water at different temperatures and in NaOCl at 37˚C and 60˚C [12].

The results showed that Reciproc Blue exhibited higher cyclic fatigue resistance under all conditions.

Immersion in NaOCl at 60˚C had a negative impact on the cyclic fatigue resistance of all instruments except Reciproc Blue, whereas immersion in distilled water at 60˚C increased the cyclic fatigue resistance of Reciproc Blue. Overall, the heat-treated files demonstrated higher fatigue resistance than traditional files.

In conclusion, high NaOCl temperatures negatively affected the fatigue life of the file systems, whereas the heat-treated files showed a longer fatigue life [12].

Another study by Alfawaz *et al*. in 2018 tested the cyclic fatigue resistance of heat-treated instruments immersed in NaOCl solution at different concentrations and under different temperature conditions [13].

Using a set of 135 ProTaper Gold F2 instruments, divided equally into 9 groups of 15 instruments each, cyclic fatigue tests were carried out using a block containing artificial canals with a curvature of 60˚, a radius of curvature of 5 mm, and a center of curvature located 5 mm from the tip of the instrument. This block was fixed inside a container filled with distilled water, 2.5% NaOCl or 5.25% NaOCl. Temperatures were initially set at 25˚C, 37˚C or 60˚C; the instruments were then rotated at a speed of 300 rpm until failure. The number of cycles to failure was thus calculated, the length of the fragment was measured, and the fracture surfaces were examined under a scanning electron microscope, which led to the conclusion that an increase in the ambient temperature of the NaOCl reduces fatigue resistance [13].

4.2.3. Cyclic Fatigue Resistance According to Concentration

The effect of EDTA and NaOCl concentrations on the cyclic fatigue of nickel-titanium files is the third point to be considered in the chapter "Comparison of cyclic fatigue resistance during immersion in EDTA and/or NaOCl". Varying concentrations of EDTA can potentially compromise the stability of nickel-tita-

nium files by altering their structural and mechanical properties. At the same time, high concentrations of hypochlorite can cause undesirable corrosion-type reactions with nickel-titanium, which can affect the cyclic fatigue resistance of these instruments.

Thus, a study by Hasegawa, Goto and Ogura evaluated the impact of two EDTA concentrations (3% and 10%) on the corrosion fatigue of three NiTi files of distinct shapes (Flex Master, RaCe and K3), comparing them with other solutions (6% NaOCl, 3% H_2O_2, 0.9% NaCl and distilled water). The NiTi files were subjected to rotating bending in a curved glass tube with bending angles of 30˚ and 60˚, while immersed in the solutions, and the number of rotations to failure was recorded. At a bending angle of 30˚, the files in both EDTA solutions showed significantly lower resistance than those immersed in distilled water; however, no notable difference was identified between the two EDTA solutions (3% and 10%). The FM file showed significantly lower resistance in the EDTA solutions compared with the 3% H_2O_2 solution, whereas the other two files, RC and K3, showed no significant difference between the five solutions tested (3% EDTA, 10% EDTA, 6% NaOCl, 3% H_2O_2 and 0.9% NaCl).

At a bending angle of 60˚, early failure occurred between 1 and 2.5 minutes for all the files evaluated, and no significant difference was observed between the six solutions.

The results of the study indicated that corrosive solutions reduce the fatigue resistance of the files tested, with EDTA solutions potentially having a more marked impact on fatigue resistance [14].

In contrast to this study, Erik and Özyürek randomly divided NiTi files into 5 groups before placing them in the following solutions: distilled water, 6% NaOCl, 17% EDTA, 18% HEBP; and 6% NaOCl combined with 18% HEBP. They concluded that EDTA, NaOCl and HEBP solutions have no effect on cyclic fatigue resistance when used alone. In contrast, the combination of NaOCl and HEBP solutions reduced cyclic fatigue resistance [15].

Another study by Alfawaz *et al*. in 2022 compared the cyclic fatigue resistance of EdgeTaper Platinum (ETP) and ProTaper Gold (PTG) instruments with different irrigating solutions, namely 17% EDTA and 5.25% NaOCl. The researchers found that ETP showed improved cyclic fatigue resistance compared with PTG in all irrigating solutions tested, and that EDTA can be used in combination with NiTi instruments during canal preparation without compromising the cyclic fatigue resistance of PTG and ETP instruments, whereas NaOCl drastically decreased the number of cycles to fracture of both systems [16].

4.3. Comparison of File Surface Topography during Immersion in EDTA and NaOCl

Irrigating solutions, particularly NaOCl, are used for their ability to remove organic debris and dissolve pulp tissue. At the same time, chelating agents, such as EDTA, help remove mineral deposits, thereby facilitating the cleaning of root ca-

nals. The interaction between these chemical solutions and NiTi files is crucial, because it can influence the performance of the instruments in terms of flexibility, fatigue resistance and incidence of fracture. Understanding this dynamic makes it possible to optimize endodontic protocols by adjusting the parameters of use of these agents to better suit the characteristics of NiTi files. Ongoing research in this field aims to refine clinical practice and to develop more effective canal preparation strategies.

A recent study by Pallewar *et al.* examined the effect of EDTA and NaOCl on file topography, using AFM to evaluate the effect of immersion in NaOCl (5.25%) and EDTA (17%) solutions. A total of 81 NiTi instruments (27 of each of three brands) were analyzed, divided into three groups:

- Group 1: ESX (Brasseler, USA)
- Group 2: TruShape (Dentsply Tulsa, USA)
- Group 3: ProTaper Gold (Dentsply Tulsa, USA)

Each group was divided into three subgroups, each containing nine instruments. The subgroups were:

- Group a: not immersed
- Group b: immersed in 5.25% NaOCl for 5 minutes
- Group c: immersed in 17% EDTA for 5 minutes

Using fine orthodontic pliers, the active part of the instruments—the 3 mm closest to the apical end—was separated. Nine active segments from each group were kept as controls; nine other active segments from each group were immersed in 5.25% NaOCl for 5 minutes; and the last nine active segments from each group were immersed in 17% EDTA for 5 minutes. After 5 minutes of immersion, the samples were dried. The non-immersed and immersed instruments were then mounted on a silicon wafer using a fast-drying cyanoacrylate adhesive [17].

The surfaces along 3 mm sections at the instrument tips were analyzed by AFM in contact mode under ambient conditions, and the data were then analyzed by two-way analysis of variance (ANOVA) and pairwise comparisons of the three main groups regarding Ra and RMS roughness values [17].

The three-dimensional AFM images revealed that the roughness values (Ra and RMS) of the non-immersed ESX, TS and PTG instruments were significantly lower than those of the instruments immersed in 5.25% NaOCl or 17% EDTA. ESX instruments showed the highest roughness values, followed by PTG instruments and then TS instruments.

For the instruments immersed in 5.25% NaOCl for 5 minutes, the Ra and RMS values were highest for TS instruments, followed by PTG instruments and ESX instruments. For the instruments immersed in 17% EDTA for 5 minutes, the Ra and RMS values were highest for ESX instruments, followed by PTG instruments and TS instruments [17].

The results of this study suggest that short-term contact between 5.25% NaOCl or 17% EDTA solutions and NiTi instruments can cause alterations in the surface topography of the instruments, and that these alterations could affect the perfor-

mance and lifespan of the instruments.

Consequently, the immersion of NiTi rotary instruments in cleaning and disinfecting solutions should be limited in time [17].

Prasad *et al*. also conducted a study consistent with the previous one, using eight NiTi rotary instruments: four ProTaper-S2 (Dentsply) and four iRaCe-R3 (FKG DENTAIRE). Three of the four instruments of each type were immersed separately and respectively in 5% NaOCl, 17% EDTA and Triphala for five minutes [18].

"Triphala" is a well-known powdered preparation from Indian medicine. It is composed of equal parts of Emblica officinalis, Terminalia chebula and Terminalia belerica. Among its benefits are antifungal and antiviral activity; it has also demonstrated antimutagenic/anticancer activity, antioxidant activity, adaptogenic and anti-anaphylactic activity, immunomodulatory activity, as well as cytoprotective and radioprotective activity, which makes it an interesting alternative for canal irrigation given the many undesirable characteristics of NaOCl [19]. After immersion in the test solutions, the instruments were air-dried at room temperature. Two instruments—one ProTaper and one iRaCe—were kept without immersion as controls; the instruments were then fixed on a metal support using adhesive tape, and nine surface areas were analyzed on a 3 mm cross-section taken from the center of the instruments [18].

After microscopic analysis by AFM, nanoscale topographic irregularities were observed for all instruments. The instruments immersed in EDTA and NaOCl showed significantly higher surface roughness than the untreated instruments. iRaCe instruments immersed in NaOCl showed the highest surface roughness, whereas ProTaper instruments immersed in Triphala showed the lowest surface roughness [18].

The results of this study suggest that short-term contact with 17% EDTA and 5% NaOCl, a powerful oxidizing agent, can be corrosive to metals. In contact with a NiTi rotary instrument, NaOCl can cause selective removal of nickel from the surface of the instrument, leaving areas of exposed titanium, which leads to micropitting and, consequently, significant deterioration of the surface of NiTi rotary instruments [18].

Furthermore, a study by Sağlam *et al*. concluded that the use of 2.5% NaOCl could be recommended to prevent weakening of the ProTaper file, which shows less surface damage compared with the use of 5% NaOCl and the MTAD solution [20].

The researchers found that the RMS values of all treated samples were higher than those of the control sample, and that, among the NaOCl-treated files, the NiTi file treated with 5% NaOCl showed the highest surface roughness, whereas the NiTi file treated with 2.5% NaOCl showed slightly lower surface roughness. Among all the treated samples, the NiTi file treated with the MTAD solution showed the highest surface roughness, whereas the NiTi file treated with chlorhexidine (CHX) showed the lowest surface roughness [20].

It should be noted that MTAD, an endodontic irrigant composed of a mixture of doxycycline (a tetracycline isomer), citric acid and a detergent, demonstrates convincing antimicrobial efficacy in the laboratory; however, this efficacy decreases when clinical conditions are simulated. MTAD nevertheless remains an excellent agent for removing the smear layer alongside NaOCl, and its ability to dissolve pulp tissue is an advantage [21].

Corrosion of the surface of endodontic instruments, resulting from chemical reactions with irrigants, causes surface irregularities and can lead to premature failure. In addition to their beneficial effects during canal preparation, such as lubrication, tissue dissolution and removal of the smear layer, irrigating solutions can have undesirable effects on the surface of the instruments, reducing their resistance [20].

In conclusion, the 2.5% and 5% NaOCl irrigating solutions, as well as the MTAD solution, caused surface alterations on ProTaper NiTi files. Thus, increasing the NaOCl concentration increases the surface roughness of the files [20].

However, a study by De Castro Martins *et al*. used 80 instruments randomly divided into 4 groups. The first group was simply immersed in a 5.25% NaOCl solution for 24 hours; the second and third groups of files were used to shape the mesial canals of 50 extracted mandibular molars; and a fourth group served as a control. However, the irrigation method differed: the second group used deionized water, whereas the third group used 5.25% NaOCl [22].

This experiment led to the conclusion that immersion in 5.25% NaOCl for 24 hours did not modify the surface characteristics or the fatigue resistance of the instruments tested; however, the simulated shaping performed by the files of groups 2 and 3 was a determining factor in reducing the number of cycles to failure measured during the fatigue tests. Furthermore, the use of NaOCl during the shaping of curved canals reduced instrumentation time and increased the lifespan of the instruments; as a result, instruments used with NaOCl tended to have a longer lifespan than those used without NaOCl [22].

By exposing XP-endo Shaper (XPS) and TruNatomy (TN) instruments to a NaOCl and EDTA solution according to standard endodontic protocols, Jose *et al*. were able to compare the effects of the two irrigating agents on endodontic instruments, concluding that surface roughness was lower for XPS compared with TN, and that a 17% EDTA concentration resulted in significantly higher surface roughness for both file systems compared with a 5.25% NaOCl concentration [23].

Another study by Hamdy *et al*. used five types of NiTi endodontic rotary instruments: ProTaper Next, Hyflex CM, Hyflex-EDM, WaveOne Gold and TruNatomy. These instruments were examined by SEM to ensure that they were neither deformed nor defective. Ten instruments of each brand were first analyzed by AFM; the instruments were then rotated in 5.25% NaOCl for 15 minutes, with speed and torque set according to the manufacturers' instructions [24].

After this exposure, the instruments were rinsed with distilled water and dried, then analyzed again by AFM [24].

The experiment demonstrated that TruNatomy and ProTaper Next instruments showed the lowest surface roughness, and that all the NiTi endodontic rotary instruments tested after exposure to irrigants showed an increase in surface roughness [24].

To compare the effect of immersion in NaOCl on the surface characteristics of two nickel-titanium rotary instruments using AFM, Topuz *et al.* used four RaCe NiTi rotary files, dividing them into two groups: Group 1 (NaOCl immersion): one 30.06 file and one 30.02 file were immersed in a 5.25% NaOCl solution for 5 minutes. Group 2 (Control): one 30.06 file and one 30.02 file were kept as controls without immersion in NaOCl.

In summary, it was found that NaOCl caused surface degradation of RaCe instruments [25].

Another study was conducted by Cai *et al.* using 36 files of each brand, HyFlex and M3. These instruments were subjected to different immersion protocols: 5.25% NaOCl and 17% EDTA; an analysis of variance was then used to compare the number of rotations to failure. Through this experiment, the researchers found that the surface roughness of M3 files exposed to irrigants had increased compared with HyFlex files immersed in NaOCl; however, they also found that a change in the surface topography of the instruments caused by 10 minutes of contact with the irrigants did not lead to a decrease in cyclic fatigue resistance [26].

4.4. Comparison of File Corrosion during Immersion in EDTA and NaOCl

Corrosion of nickel-titanium (NiTi) files is a fundamental issue in endodontics, particularly with regard to the complex interactions with chemical agents such as irrigants and chelating agents. NaOCl, owing to its oxidizing power, can induce corrosion of NiTi files. The electrochemical reactions associated with the release of metal ions can alter the crystal structure and mechanical strength of the files. EDTA, although mainly used as a chelating agent to remove calcium deposits, can also influence corrosion by facilitating the exposure of the NiTi file surface to corrosive agents.

The release of metal ions resulting from corrosion can have clinical implications such as embrittlement of the files, the generation of metal particles likely to irritate periapical tissues, and a reduction in the lifespan of the instruments. Research continues to aim for a deeper understanding of the molecular and electrochemical mechanisms underlying the corrosion of NiTi files, in order to guide the development of more corrosion-resistant alloys and to optimize protocols for the use of chemical agents in endodontics.

In 2008, Bonaccorso *et al.* conducted a study to evaluate the corrosion resistance of nickel-titanium (NiTi) rotary instruments subjected to various surface treatments.

Three groups of instruments were studied:

- Group A: electropolished RaCe instruments

- Group B: non-electropolished RaCe instruments
- Group C: Alpha files coated by physical vapor deposition (PVD)

Each group comprised 10 instruments. The instruments were exposed to solutions containing 17% EDTA or NaCl.

Electrochemical measurements were then carried out using a potentiostat, a device that allows the precise study of electrochemical reactions and electrode properties. In this study, it was used to measure the galvanic current, revealing that no localized corrosion was observed in the EDTA solution for any of the three groups of instruments [27]. In contrast, in NaCl, the corrosion potential was higher for the electropolished and PVD-treated instruments, indicating increased corrosion resistance. A potential risk of corrosion appears to exist for NiTi instruments that have undergone no surface treatment and come into contact with NaCl [27].

In conclusion, NiTi instruments treated by PVD and electropolishing show increased corrosion resistance [27].

Furthermore, Cheung and Darvell concluded that the rotating-bending fatigue resistance of NiTi rotary instruments is brand-dependent and is influenced by NaOCl, which corrodes NiTi instruments by creating microcracks on their surface [28].

Oktavia *et al.* compared the effect of 2.5% NaOCl combined with either 17% EDTA or 0.2% high-molecular-weight chitosan on the corrosion of ProTaper Universal and iRaCe rotary instruments used to prepare 24 extracted human premolars. The combination of 2.5% NaOCl and chitosan reduced corrosion and surface defects compared with the combination of NaOCl and EDTA, which suggests that chitosan could be developed as an alternative chelating agent to EDTA [29]. Chitosan is a natural biopolymer derived from chitin that has unique characteristics such as biocompatibility, degradability and broad-spectrum antibacterial activity, making it a versatile material for various oral health applications [30].

5. Conclusions

This study thoroughly examined the behavior of nickel-titanium alloy files in the presence of irrigants, focusing in particular on the role of NaOCl and EDTA solutions.

Overall, the results of the included studies are heterogeneous. NaOCl used at room or body temperature and for short exposures did not reduce cyclic fatigue resistance in several studies, whereas heated, concentrated or prolonged exposure to NaOCl reduced it in others; EDTA reduced cyclic fatigue resistance in some studies after prolonged exposure (more than three minutes), but had no effect in others. These effects remain modulated by the instrument alloy, its heat treatment and the kinematic motion used, which explains the divergent results observed in the included studies; these findings should therefore not be generalized beyond the specific experimental conditions in which they were obtained.

EDTA will continue to be used as a final rinse solution after canal shaping. The study also addressed specific aspects such as the cyclic fatigue of the files, the po-

tential corrosion induced by irrigants, and the topographic changes observed during their interactions with NaOCl, EDTA and other endodontic irrigants. These detailed observations provide key elements for a comprehensive understanding of the complex effects of these solutions on endodontic instruments. The results of this research thus make a substantial contribution by further clarifying the mechanisms underlying the interactions between NiTi files and irrigants, paving the way for significant improvements in clinical endodontic practice.

Limitations of the Study

It should be emphasized that this field of research remains largely unexplored, which reinforces the importance and relevance of the present study. In addition, this research highlights a gap in the scientific literature by pointing out the lack of studies devoted to the influence of the different forms of EDTA on the behavior of NiTi files. It is therefore essential to continue investigations in order to understand how variations in the composition and form of EDTA may influence the properties of files used in endodontics. In addition, methodological quality was appraised by a single evaluator from the extracted data rather than from the full texts, so that the ratings, notably for randomization and statistical analysis, are probably under-reported; all the included studies are *in vitro* and heterogeneous in design, which precluded any quantitative synthesis.

Author Contributions

Each author made a significant contribution to the completion of this review. AT, KB, MD and RMA designed and conducted the study. AT, KB, MD and RMA searched the electronic databases, selected the articles, extracted the data, synthesized the results and wrote the first draft of the manuscript with input from FZR. All authors read, reviewed and approved the final version of the manuscript.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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