REVIEW ARTICLE

Incidence of Different Types of Intracanal Fracture of Nickel–Titanium Rotary Instruments: A Systematic Review

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Abstract

Aim: The aim of this systemic review is to investigate these parameters by analyzing the characteristics of fractured instruments to determine which is the most relevant mechanical stress that induces intracanal separation *in vivo*.

Background: The fracture of nickel–titanium (Ni–Ti) instruments is a result of flexural fatigue and torsional fatigue. An electronic search was conducted in MEDLINE database, Web of Science, and Cochrane following preferred reporting items for systematic reviews and meta-analyses guidelines. Data were collected and the key features from the included studies were extracted. Overview quality assessment questionnaire scoring assessed the quality of the articles. A total of 12 articles were selected, where the lowest score was 13.

Review results: Considering Ni–Ti rotary instruments, this overall evaluation comprehends 939 broken instruments with an incidence of fracture of 5%. Out of the 12 selected articles, 10 studies revealed that flexural failure was the predominant mode (range of 62–92%). It appears that motion plays an important role when it comes to mechanisms of fracture. The majority of defects found in hand-operated instruments were in the form of torsional failure. Although the major cause of separation of rotary instruments is flexural fatigue, smaller instruments show more torsional fracture than the larger instruments. The average fragment length was found to be 2.5 mm and 3.35 mm, respectively, for torsional failure and flexural failure. The risk of bias depends on fractographic analysis.

Conclusion: Flexural fatigue is the predominant mode of fracture in rotary Ni–Ti instruments. The type of motion and size of the instrument seem to affect the mechanism of fracture. Fragment length may show a strong association with the type of fracture mechanism.

Clinical significance: This systemic review found that flexural fatigue is the most relevant mechanical stress that induces intracanal separation *in vivo*. Moreover, in clinical practice, the fragment length might be an excellent indicator of the type of fracture.

Keywords: Flexural stress, Fracture, Instrument design, Rotary nickel–titanium instruments, Torsional stress.

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Background

Despite the numerous advancements in the last decades in nickel–titanium (Ni–Ti) instrument design and metallurgical properties, instrument separation is still a concern in root canal therapy. It can impede the microbial control beyond the obstruction, significantly reducing the outcome of the root canal treatment especially when the retained fragment is inside an uncleaned canal harboring bacteria.[1,2]

It has been recognized that flexural and torsional stresses are the major mechanisms involved with instrument separation during clinical use.[3] Flexural fatigue takes place after repeated cycles of tension and compression, reported at an area of maximum curvature when the instrument rotates in a curved canal. Torsion stress is generated when the instrument twists along its longitudinal axis or when the tip of the instrument becomes locked while the shank continues to rotate. In many cases, the two mechanisms act simultaneously during instrumentation, with any instrument progression inside a curvature subjected to torsional stress. Similarly, there are very few perfectly straight canals; small degrees of curvatures are often present. As a consequence, the amount and the proportion of flexural and torsional stresses are highly variable. It depends on different anatomical complexities, predominantly curvatures and canal diameters, but it is also related to the Ni–Ti rotary instruments' characteristics and dimensions.[4,5]

A huge number of studies have been conducted in order to assess the different factors and mechanisms involved with instrument fracture. However, the great majority (approximately 90%) of these have been performed *in vitro*. While it is easier to select the parameters to be investigated in "*in vitro*" studies, much contradictory information is apparent during "*in vivo*" studies. The clinical studies are influenced by many variables: the use of instruments in different canals and anatomy; the use of instruments

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with different designs, dimensions, and tapers; and the use of different motions or different operative parameters.[6] All of these factors lead to different results. Moreover, the study designs are also variable and therefore the collected data may not be homogeneous.

Such controversial results lead to the need for clarification about the prevalence of the kind of Ni–Ti clinical failure, and consequently a systematic review about the topic. In fact, the majority of clinicians still fear sudden, unexpected intracanal separation of Ni–Ti rotary instruments and do not comprehend what is the main reason for such failures. The aim of this systemic review is to investigate, by analyzing the characteristics of fractured instruments and the different related parameters, to determine the most relevant mechanical stress that induces intracanal separation "*in vivo*".

Method

Protocol and Registration

This systematic review has been conducted based on preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines.[7] The focused question for this review was: which type of stress can be considered as the major cause of instruments' intracanal separation? The null hypothesis is that there is no difference between torsional and flexural fracture incidence.

Literature Search

An exhaustive search was undertaken to identify all *in vivo* clinical studies that involved separated instruments. The MEDLINE database, Web of Science, and Cochrane were searched by using "broken instrument" OR "fractured instrument" OR "separated instrument" OR "clinical" OR "*in vivo*" OR "technical quality" OR "iatrogenic errors" OR "flexural/bending stress" OR "fatigue/torsional stress" as keywords. The search of the MEDLINE database included all years from 2000 until March 2020. A similar strategy was also applied by using Web of Science and the Cochrane database. In addition, a forward manual search was also conducted on the reference list of the selected articles.

Study Selection and Data Extraction

From search results, titles and abstracts of articles were screened by two independent authors. The full-texts of relevant studies were reviewed according to the eligibility criteria. A systematic data extraction sheet was constructed. From the selected studies, the following criteria were recorded: name and impact factor of the journal where the study was published, sample size, the incidence of instrument separation, type of fracture (torsional or flexural), instruments characteristics (motion, brand, size, and taper), location of the fracture, deformation rate, fragment lengths, and anatomy characteristics (curvature and radius and number of teeth).

Eligibility Criteria

Criteria for the selection of studies were established before the literature search. A summary of inclusion and exclusion criteria is detailed in Table 1.

Risk of Bias and Quality of Evidence

Review quality was rated independently by two authors. The risk of bias in selected studies was evaluated using an overview quality assessment questionnaire (OQAQ) scoring for each article.[8] Nine questions with a score range from 0 to 18 were designed to fulfill these quality assessment criteria. Articles with an OQAQ score ≥12 (approximately 75% or more of total points) were of high quality and were included in this systematic review.

Table 1: Summary of inclusion and exclusion criteria

Exclusion criteria	*Inclusion criteria*
In vitro studies	*In vivo* clinical studies
Studies with endodontic treatment performed using only stainless steel instruments	Studies with intracanal breakage instrument
Studies that do not evaluate the torsional mechanism of fracture	Studies that evaluate torsional/flexural fracture
Studies that do not evaluate the flexural mechanism of fracture	Studies in which root canal treatment was performed by engine-driven or hand Ni–Ti instrumentation
Studies conducted using permanent teeth without complete root formation or primary teeth	Studies that examined separated instruments using stereomicroscope or scanning electron microscope
Reviews, case reports	Studies that assessed the quality of root canal treatment on human patients
Studies based on questionnaire survey	Studies performed by undergraduate students, residents, or endodontists

Results

The initial search strategy yielded 451 references after removing duplicates of different searched databases. Following a preliminary screening assessed and based on the abstracts and titles, the references were reduced to 61 manuscripts found in the reference section (Fig. 1).[3,9–68] The full texts of the remaining articles were then obtained and revised by two authors. Only *in vivo* studies that evaluated torsional/flexural stresses were included in the systematic review. Other main reasons for the exclusion of references were mainly *in vitro* studies, endodontic treatments performed only with stainless steel instruments, articles based on a questionnaire survey, and review or systematic review on any topic. Furthermore, from the remaining references, a limit of ten observed instruments was set. For that reason, two more articles were excluded because the observed number of fractured instruments was, respectively, 5, 2, and 2.[41,44,45]

Moreover, Shen et al. part 1 and part 2 are based on the same sample, therefore, will be considered as one reference.[16,17] Of those 61 references, 12 were eligible to be included in quantitative analyses due to similarities between them allowing for statistical comparison (Table 2).

The risk of bias is indicated in Table 3, and it depends on fractographic analysis, more specifically on the technique used for observations and the numbers of operators involved in the observation process.

Discussion

The fracture of Ni–Ti instruments is a result of flexural fatigue and torsional fatigue. The low-power microscopic longitudinal examination of the instrument reveals the mechanism of instrument fracture.[3] All the 12 selected articles evaluated the presence of

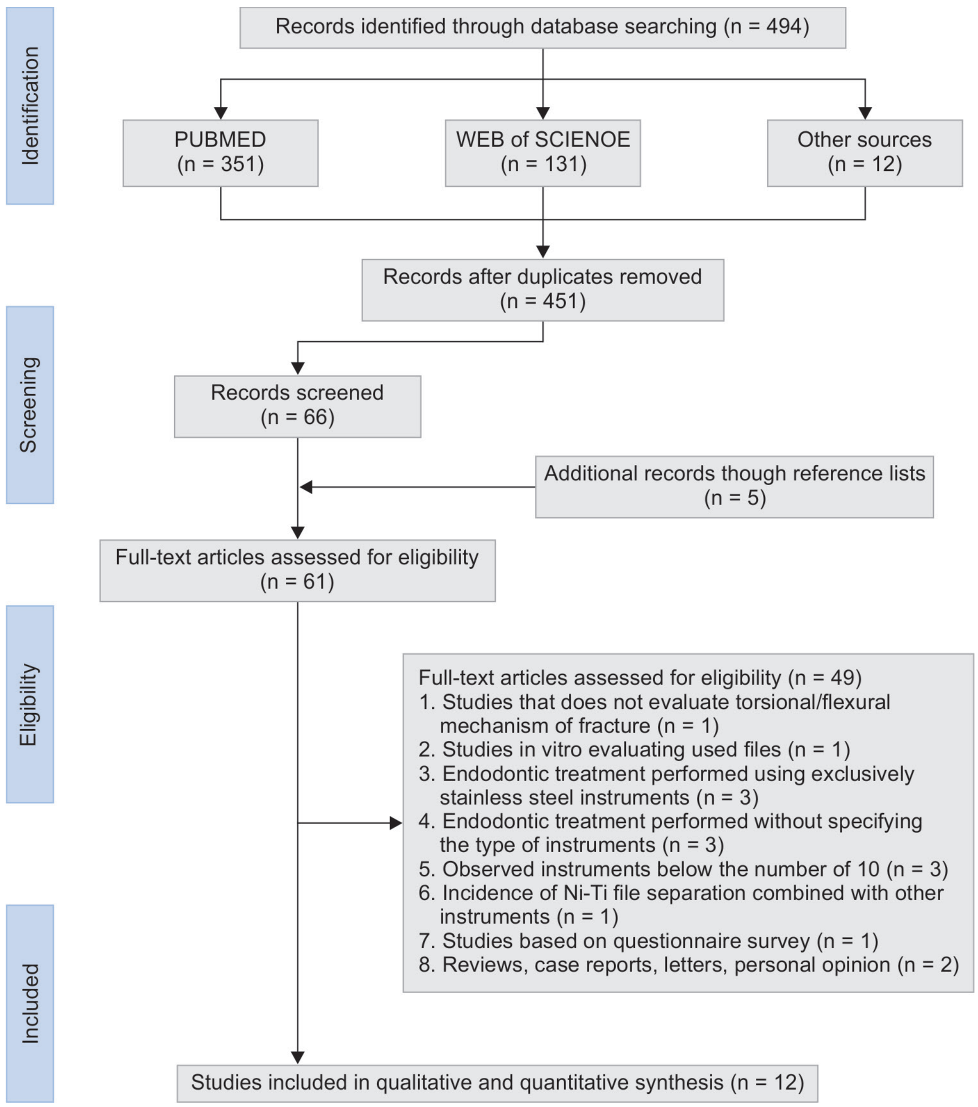

Fig. 1: PRISMA flow diagram

plastic deformation in lateral view and categorized them into either torsional or flexural failure according to Sattapan et al.[3] The observation was done using mainly stereomicroscope at magnification 10–40×.

More specifically, flexural fatigued instruments show no evidence of plastic deformation. The surface of the fractured instrument due to fatigue failure is unique and characterized by linear striations and areas of crack initiation. Torsional fatigue occurs when the instrument twists along its longitudinal axis or when a part of the instrument (generally the tip) gets locked while the shank continues to rotate. Subsequently, the instrument that fractures due to torsional fatigue will show evidence of plastic deformation such as unwinding, characterized by inhomogeneous crystals that appear as localized nods and circular abrasion marks straightening, reverse winding, and twisting.[3,13] Therefore, the observation of the instrument in lateral view is as important as the observation of the fractured surface in order to detect unique characteristics of the mechanisms of failure.[9] For instance, fatigue striations are unique to fatigue and can be observed on the fracture surface but not in lateral view. When comparing the mode of examination, two studies[9,21] showed that fractographic examination of the fractured surface at high magnification was a better method of revealing the mechanism of instrument failure. Six of the twelve studies observed the fractured instruments in lateral view, using stereomicroscope but also examined the fracture surface under scanning electron microscopy (fractography examination) to complete the analysis.[9,10,12,18,19,21]

Different ways to do the evaluation are possible, but in all cases, the determination of the mechanisms of fracture is based on the interpretation of the examination. Therefore, the evaluation by two investigators is essential in order to reduce the risk of bias. In the majority of the studies, the interpretation of the images was done by one evaluator. In only two studies,[9,21] two examiners performed the fragment analysis.

It is not easy to determine which type of stress (flexural vs torsional) has a major role in determining intracanal failure, as both may be present. The results of the present systematic review provided an answer to the focused question, describing which type of stress was considered as the major cause of instruments' intracanal separation. Out of the 12 selected articles, 10 studies revealed that

Table 2: Studies eligible for the review

Study	Sample	Country of origin	Type of study	No. of fractured instruments	Incidence of fracture (%)	Type of fracture		Length of fragment		Size of instruments	
						Torsional stress	Flexural stress	Torsional stress	Flexural stress	Torsional stress	Flexural stress
Cheung et al.[9]	122	China	Retrospective	28	23	33% (9/27)	66% (18/27)	2.5 ± 0.8	4.3 ± 1.9	N/A	N/A
Cheung et al.[10]	325	China	Retrospective	44	14	33% (15/44)	67% (29/44)	2.5 ± 1.1	4.1 ± 1.6	N/A	N/A
Fernández-Pazos et al.[11]	571	Spain (N/A)	Retrospective	43	7.5	21% (9/43)	79% (34/43)	N/A	N/A	17.04 ($n = 25$) 25.06 ($n = 5$) 30.07 ($n = 4$)	17.04 ($n = 7$) 25.06 ($n = 2$)
Inan et al.[12]	593	Turkey (N/A)	Retrospective	95	16	28% (27/95)	72% (68/95)	N/A	N/A	10.04 ($n = 13$) 15.05 ($n = 10$) 20.06 ($n = 4$)	10.04 ($n = 18$) 15.05 ($n = 12$) 20.06 ($n = 13$) 25.06 ($n = 15$) 30.05 ($n = 5$) 35.04 ($n = 2$) 25.07 ($n = 3$)
Parashos et al.[13]	7159	Australia and New Zealand (N/A)	Retrospective	353	5	29% (103/353)	71% (250/353)	1.3 ± 0.9	2.8 ± 2.2	N/A	N/A
Peng et al.[14]	121	China	Retrospective	27	22	7.5% (2/27)	92.5% (25/27)	3.77	3.66	N/A	N/A
Shen et al.[15]	166	Canada	Retrospective	12	7.2	33% (4/12)	66% (8/12)	1.88 ± 0.8	3.31 ± 1.2	0.06 ($n = 1$) 0.04 ($n = 3$)	0.06 ($n = 3$) 0.04 ($n = 5$)
	325	Canada	Retrospective	45	13.8	4% (2/45)	96% (43/45)	N/A	N/A	S1 ($n = 2$)	S1 ($n = 26$) SX ($n = 9$) S2 ($n = 6$) F1 ($n = 1$) F2 ($n = 1$)
Shen et al.[16,17]	621	Canada	Retrospective	25	4	48% (12/25)	52% (13/25)	3.0 ± 1.1	3.6 ± 1.2	Shaping ($n = 12$)	Shaping ($n = 9$) Finishing ($n = 4$)
	487	Canada		34	7	18% (6/34)*	76% (26/34)*			Shaping ($n = 4$) Finishing ($n = 2$)	Shaping ($n = 22$) Finishing ($n = 4$)
	294	Canada		9	3	0%	78% (7/9)*			N/A	N/A
Shen et al.[18]	3706	Canada	Retrospective	12	0.3	83% (10/12)	16% (2/12)	2.7 ± 1.5	2.9 ± 4.7	20.04 ($n = 10$)	30.04 (n=1) 20.04 (n=1)
Shen et al.[19]	414	Canada	Retrospective	26	6.2	85% (22/26)	15% (4/26)	2.87 ± 1.6	2.16 ± 0.8	25.08 ($n = 4$) 25.06 ($n = 6$) 25.04 ($n = 11$) 25.02 ($n = 1$)	25.08 ($n = 1$) 25.06 ($n = 2$) 25.04 ($n = 1$)
Shen et al.[44]	2397	Canada	Retrospective	86	3.6	36% (31/86)	64% (55/86)	N/A	N/A	0.08 ($n = 6$) 0.06 ($n = 13$) 0.04 ($n = 11$) 0.02 ($n = 1$)	0.12 ($n = 3$) 0.10 ($n = 9$) 0.08 ($n = 14$) 0.06 ($n = 16$) 0.04 ($n = 13$)
Wei et al.[21]	774	China	Retrospective	100	13	12% (12/100)	88% (88/100)	N/A	N/A	SX ($n = 3$) S1 ($n = 8$) F1 ($n = 1$)	SX ($n = 15$) S1 ($n = 21$) S2 ($n = 14$) F1 ($n = 15$) F2 ($n = 22$) F3 ($n = 1$)

*The score was given according to the following: yes (2), partially/cannot tell (1), no (0)

Table 3: Risk of bias. The Greaves et al. (2011) adaptation of the overview quality assessment questionnaire used to assess the quality of articles

Question / *Study*	*Cheung et al.*[9]	*Cheung et al.*[10]	*Fernández-Pazos et al.*[11]	*Inan et al.*[12]	*Parashos et al.*[13]	*Peng et al.*[14]	*Shen et al.*[15]	*Shen et al.*[16,17]	*Shen et al.*[18]	*Shen et al.*[19]	*Shen et al.*[44]	*Wei et al.*[21]
Was the hypothetical question well stated?	2	2	2	2	2	2	2	2	2	2	2	2
Was the methodology detailed in a comprehensive way?	2	2	2	2	2	1	2	2	2	2	2	2
Were the inclusion and exclusion criteria well defined	2	2	2	2	2	2	2	2	2	2	2	2
Were bias covered by examiners?	2	0	0	0	1	0	1	1	1	0	0	2
Were the instruments examined under magnification?	2	2	2	2	2	2	1	1	2	2	2	2
Was the statistical analysis used in the study?	1	2	2	2	2	0	2	2	0	1	2	0
Were the methods used relevant to reach a conclusion?	2	2	2	2	2	2	2	2	2	2	2	2
Were the findings relative to the primary question?	2	2	2	2	2	2	2	2	2	2	2	2
Were the conclusions made by the author(s) supported by the data?	1	2	2	2	2	2	2	2	1	2	2	2
Total score	16	16	16	16	17	13	16	16	14	15	16	16

flexural failure was the predominant mode of fracture with a range of 62 to 92%. On the contrary, two articles showed that torsional failure was the predominant one.[18,19] Shen et al.[41] part 3 found that 83% of the instruments failed mainly because of torsional stress. The latter results can be explained by the fact that the root canal therapy was performed by inexperienced operators (undergraduate students). The application of excessive force beyond the yield point of the material undergoes plastic deformation of the instrument and consequently its failure.[18,19] Also, Shen et al.,[16] part 4 analyzed electropolished (race) instruments and found that torsional failure was responsible for 85% of the fracture of the instruments. The authors explained the previous result by the smoother surface finish with a reduction of inclusions that improve the mechanical properties of Ni–Ti alloy, more specifically resistance to cyclic fatigue.[19]

Considering Ni–Ti rotary instruments, this overall evaluation comprehends 939 broken instruments of 18,000 collected instruments with an incidence of fracture of 5%. The most relevant study was conducted by Parashos et al. with more than 7000 examined instruments, who showed 75% flexural and 25% torsional failure rate. They also suggested that instrument fracture is a complex, multifactorial clinical problem.[13] The most important variables on instrument failure were the operator and root canal anatomy being more influential than the instrument itself. Also, Shen et al., part 1 showed that the fracture appears to be influenced by the operator and the preparation technique.[16] On the other hand, Shen et al. suggested that the design of the instrument is an important factor affecting the type of instrument separation.[15] None of the 12 examined studies evaluated the impact of curvatures on the separated instruments.

In the studies, when specified, the instruments were used according to the manufacturer's recommendations. Therefore, different speeds and different torque were used making it impossible to compare these variables. However, two of the studies compare the failure mode of the same instruments in hand-operated and rotary motion. It appears that motion plays an important role when it comes to mechanisms of fracture. The majority of defects found in hand-operated instruments were in form of torsional failure, whereas the majority of rotary instruments failed because of fatigue.[13] Cheung et al. compared ProTaper instruments in different motions and found that 67% of rotary instruments failed because of flexural fatigue while 62% of hand-operated instruments failed because of torsional fatigue.[10] Accordingly, the results of Shen et al. part 1 indicated that the torsional failure predominated in hand instruments (91% of Ni–Ti hand instruments), whereas most of the rotary instruments (66% of rotary ProTaper) failed because of flexural fatigue.[16] Increasing the rotation rate generates increased crystallographic slip because there is little time for the martensitic transformation to occur.[69] Therefore, when compared to a hand-operated instrument, failure happens in a more 'brittle' way for rotary instruments. Also, the load cycles being the main determinant of fatigue life of the material seems to be reduced in the instruments operated by hand, thus reducing the fracture due to flexural fatigue.[70,71]

Generally, torsional failure of instruments decreases and flexural failure increases as the size of the instrument increases.[22] In the study of Inan, although the major cause of separation of instruments was flexural fatigue, the smallest instruments (#10.04 and #15.05 files) showed more torsional fracture and/or deformations than the larger instruments.[12] Accordingly, the study of Fernández-Pazos et al. showed that 25 #17.04 failed from shear failure while 7 from flexural fatigue. Although the major cause of separation of instruments is flexural fatigue, the smallest instruments show more torsional fracture and/or deformations than the larger instruments.[11] Also, small size instruments are more likely to lock at the tip and to fracture with less torque. Smaller instruments would be more susceptible to torsional failure than larger instruments. Therefore, it suggests that small size instruments should be considered as single-use, disposable instruments. On the other hand, large instruments exhibit more resistance in the last apical millimeters, in a situation where the tip of the instruments gets locked and less flexibility in the middle portion where the diameter of the instrument becomes greater. Therefore, large instruments are more resistant to torsional fatigue but more susceptible to cyclic fatigue suggesting that the larger and stiffer the instrument, the greater the stress during canal instrumentation, especially in curved canals.

As for the taper, Peng explained the higher number of apparent flexural' fractures than 'torsional' failure by the variable taper design of S1 ProTaper, which might have reduced the risk of taper lock fracture.[14] These findings were also confirmed by Cheung et al. and Shen et al., flexural fatigue was implicated in the majority of separations, and revealed 26 S1 ProTaper instrument fractured due to flexural fatigue while only two S1 instruments fractured from torsional fatigue.[10,15]

The lengths of the fragmented segment due to torsional failure is generally shorter than the fragment due to flexural fracture. Fatigue failure occurs where the strain is the highest, usually at the point of maximum curvature, farther from the tip of the instrument. This might explain the difference in length between torsional and flexural failure. Eight studies evaluated the impact of the mechanism of failure on the length of the fragment.[9,10,13–16,18,19] The average fragment length was found to be 2.5 $\pm$ 1.1 mm and 3.35 $\pm$ 1.9 mm, respectively, for torsional failure and flexural failure.

Conclusion

The present systematic review shows that flexural fatigue is the predominant mode of fracture in rotary Ni–Ti instruments, due to continuous elongation and compression cycles. Instrument fracture is a multifactorial problem that is affected by instrument type, size, and taper. The fragment length might be an excellent indicator for the type of fracture in clinical practice. The type of motion also seems to affect the mechanism of fracture, with more torsional failures observed in manual Ni–Ti instruments.

Clinical Significance

This systemic review found that flexural fatigue is the most relevant mechanical stress that induces intracanal separation *in vivo*. Moreover, in clinical practice, the fragment length might be an excellent indicator of the type of fracture.

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