A Structured Analysis of In Vitro Failure Loads and Failure Modes of Fiber, Metal, and Ceramic Post-and-Core Systems

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Purpose: This study sought to aggregate literature data on in vitro failure loads and failure modes of prefabricated fiber-reinforced composite (FRC) post systems and to compare them to those of prefabricated metal, custom-cast, and ceramic post systems. ***Materials and Methods:*** The literature was searched using MEDLINE from 1984 to 2003 for dental articles in English. Keywords used were (post or core or buildup or dowel) and (teeth or tooth). Additional inclusion/exclusion steps were conducted, each step by two independent readers: *(1)* Abstracts describing post-and-core techniques to reconstruct endodontically treated teeth and their mechanical and physical characteristics were included (descriptive studies or reviews were excluded); *(2)* articles that included FRC post systems were selected; *(3)* in vitro studies, single-rooted human teeth, prefabricated FRC posts, and composite as the core material were the selection criteria; and *(4)* failure loads and modes were extracted from the selected papers, and failure modes were dichotomized (distinction was made between "favorable failures," defined as reparable failures, and "unfavorable failures," defined as irreparable [root] fractures). ***Results:*** The literature search revealed 1,984 abstracts. Included were 244, 42, and 12 articles in the first, second, and third selection steps, respectively. Custom-cast post systems showed higher failure loads than prefabricated FRC post systems, whereas ceramic showed lower failure loads. Significantly more favorable failures occurred with prefabricated FRC post systems than with prefabricated and custom-cast metal post systems. ***Conclusion:*** The variable "post system" had a significant effect on mean failure loads. FRC post systems more frequently showed favorable failure modes than did metal post systems. *Int J Prosthodont 2004;17:476–482.*

Post-and-core restorations are widely used for building up endodontically treated teeth with extensive loss of hard tooth tissue. Traditionally, the custom-made cast post and core was the restoration of choice, but today, prefabricated metal and nonmetal posts combined with resin composite cores are considered viable alternatives. Post-and-core systems should provide sufficient retention for the final (crown) restoration, show acceptable fracture resistance, and add to the protection for the remaining tooth. The literature on post-and-core restorations is abundant, and numerous articles have been published investigating the above properties; failure load behavior has been studied most extensively. The information on failure load behavior is ambiguous; some studies show higher failure loads for one system compared with others, whereas other studies reveal the opposite.[1–4] A review comparing fracture resistance of prefabricated metal post systems to cast posts and cores showed no significant difference between the two types.[5]

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Table 1 Review Procedure (Selection Steps)

Step		Criteria	Information source
1	Include:	•Reconstruction of endodontically treated teeth with/without post •Mechanical and physical characteristics related to post and/or core technique (strength, fracture, failure, resistance, survival, retention, leakage, seal)	Abstract
	Exclude:	•Descriptive studies (surveys, case reports, reviews, overviews) •Primary/deciduous teeth	
2	Include:	•Articles including mention of fiber post systems	Materials and Methods
3	Include:	•Subject is in vitro failure load and failure mode •Used composite as core material (completed post-and-core restorations on "damaged" endodontically treated teeth) •Used single-rooted human teeth •Study design compared prefabricated fiber-reinforced composite posts to any other post system	Aims, Materials and Methods, Results
4		•Extraction of failure load data •Assessment and categorization of failure modes	Results

From the literature as well as from clinical experiences, it is known that fracture of the root of a post and core–reconstructed tooth is the most frequent and dramatic consequence of failure. These fractures are rarely reparable; in the majority of cases, they are considered catastrophic for the tooth, especially in the case of vertical root fractures. For this reason, not only the fracture resistance but also the topic of reparability is an increasingly important feature in evaluating post systems for clinical use. Comparable proportions of vertical root fractures are reported for custom-cast posts and cores and prefabricated metal post systems,[6,7] whereas dramatic vertical root fractures have been reported less frequently for fiber-reinforced composite (FRC) post systems.[6,8] This seems to substantiate manufacturers' claims that fiber posts show "dentin-like behavior."

A recent review focusing on fiber-based post systems attempted to find evidence justifying their use in clinical practice.[9] That study provided an appraisal of several aspects of today's knowledge about FRC posts, but did not produce aggregated data regarding fracture resistance and failure modes in comparison to other systems. The present literature study aimed to aggregate the data reported in the peer-reviewed literature on in vitro failure loads and failure modes of prefabricated FRC post systems and to compare them with prefabricated metal, custom-cast, and ceramic post systems. A structured review method was used to test two hypotheses: *(1)* Post-and-core systems with prefabricated FRC posts show similar failure loads as prefabricated metal, custom-cast, and ceramic post systems; and *(2)* post-and-core systems with prefabricated FRC posts show fewer "unfavorable failures" than do prefabricated metal, custom-cast, and ceramic post systems.

Materials and Methods

The major phases in this review were: literature search and selection, inclusion/exclusion of papers, extraction of data, and statistical analysis. The literature was searched with an electronic database (MEDLINE) with the year limits 1984 to September 2003 for dental articles written in English. Keywords used were (post or core or buildup or dowel) and (teeth or tooth). Two independent readers (a senior and junior researcher) carried out a selection of the references found on the basis of abstracts as published in MEDLINE. If no abstract was available in MEDLINE, the abstract of the original article was used. The emphasis of this first step in the review procedure was on inclusion of references, using the criteria shown in Table 1. Disagreements were resolved by discussion.

In the second step, the two independent readers selected articles in which fiber posts were mentioned in the Materials and Methods sections. References in the papers included in this step were checked by hand and cross-matched with the original list of references to add references that met the inclusion criteria. The articles were blinded by removing the Title, Authors, Journal, Introduction, and Discussion sections. Then, the selection procedure was continued by a reading of the Aims, Materials and Methods, and Results sections of the articles by the two readers independently on the basis of an additional list of selection criteria (Table 1, step 3).

In step 4, separate post-and-core systems (FRC, prefabricated metal, cast, and ceramic) were distinguished in each article, and relevant characteristics were recorded. Failure load data were extracted and expressed (if possible) in Newtons to compare the post systems. It was expected that the failure load data were too heterogeneous to allow direct pooling.

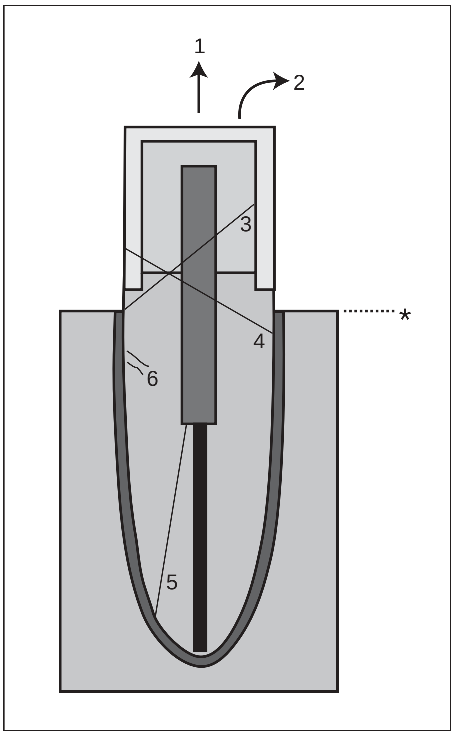

Fig 1 Failure modes: * = level of bone simulation; *1* = complete debonding of post and core (and crown); *2* = partial debonding of core/crown; *3* = fracture of post-core-tooth complex above bone level; *4* = fracture of post-core-tooth complex below bone level; *5* = (vertical) root fracture; *6* = cracks below bone level. "Favorable failure mode" = patterns 1 to 3; "unfavorable failure mode" = patterns 4 to 6.

Table 2 Reasons for Exclusion in Step 3

Reason	Study
In vivo study	King and Setchell,[15] Malferrari et al,[20] Mannocci et al,[21] Mannocci et al,[22] Ferrari et al,[23] Ferrari et al,[24] Glazer,[25] Fredriksson et al[26]
Retention study	Purton et al,[27] Qualtrough et al,[28] Gallo et al,[29] Boschian et al,[30] Dietschi et al,[31] Purton and Love[32]
Leakage study	Mannocci et al,[33] Reid et al,[34] Bachicha et al[35]
Study on dentin morphology	Ferrari et al[36]
Custom-made fiber-reinforced composite posts used	Eskitascioglu et al,[37] Rosentritt et al,[38] Sirimai et al[39]
No single-rooted teeth used	Krejci et al,[41] Mollersten et al[42]
No posts and cores made	Newman et al,[43] Mannocci et al,[44] Drummond et al[45]
No human teeth used	Isidor et al,[3] Ottl et al[46]
Endodontic access preparation only	McDonald et al[47]
Case study	Karna[40]

Therefore, it was decided to compare differences in failure loads by reassigning the differences in mean failure loads between post-and-core systems within each study to a three-point score (∂FL). If the mean failure load for FRC posts was significantly higher than that of one of the other post systems, ∂FL received a score of +1. A score of –1 was given if the mean failure load of FRC posts was significantly lower than that of the other systems. If no significant difference was reported, ∂FL = 0.

Two readers dichotomized the failure modes described in the selected articles independently. "Favorable failures" were defined as reparable failures and included adhesive failures and fractures above the level of bone simulation. "Unfavorable failures" were defined as clinically irreparable and included (vertical) root fractures (Fig 1).

In all steps, Cohen's kappa coefficient was used as a measure of agreement between the two readers. The multinomial statistical technique described by Abraham et al[10] was used to analyze reported differences in mean failure loads by testing the likelihood of significant positive (∂FL = +1) and negative (∂FL = –1) effects of the variable "FRC post" on failure load. Wilcoxon signed ranks tests were used to compare the percentages of favorable failures of the post systems within the selected studies (pairwise comparisons).

Table 3 Mean Failure Loads and Failure Modes Found in the 12 Selected Studies

Study	Sample size	Post material per system	Mean failure load*	Standard deviation	Favorable failures (%)
Studies with crown coverage					
Raygot et al[11]	10	Carbon FRC	307.00 N[a]	33.00	70
		Cast post and core	374.00 N[a]	104.00	70
		Prefabricated metal	305.00 N[a]	47.00	70
Hu et al[12]	10	Carbon FRC	287.73 N[b]	90.81	10
		Ceramic	323.82 N[b]	148.57	0
		Cast post and core	362.06 N[b]	150.63	0
		Prefabricated metal	253.01 N[b]	70.71	30
Cormier et al[13]	10	Carbon-quartz FRC	225.40 N[cde]	16.80	10
		Carbon FRC	262.80 N[cd]	22.80	10
		Glass FRC	180.00 N[e]	14.80	30
		Ceramic	238.80 N[cde]	20.40	40
		Cast post and core	207.30 N[de]	13.50	0
		Prefabricated metal	284.70 N[c]	16.40	20
Martinez-Insua et al[1]	22	Carbon FRC	1,016.95 N[f]	520.70	95
		Cast post and core	1,987.81 N[g]	1,230.73	9
Akkayan and Gülmez[6]	10	Glass FRC	744.32 N[h]	56.49	60
		Quartz FRC	894.37 N[i]	98.16	80
		Ceramic	773.84 N[h]	77.96	30
		Prefabricated metal	656.56 N[j]	81.00	0
Bolhuis et al[14]	8	Silica FRC	590.00 N[k]	190.00	†
		Cast post and core	835.00 N[l]	121.00	†
Sidoli et al[2]	10	Carbon FRC	8.89 MNm^{-2} [m]	2.40	60
		Cast post and core	15.25 MNm^{-2} [n]	4.07	0
		Prefabricated metal	14.18 MNm^{-2} [mn]	3.49	40
King and Setchell[15]	10	Carbon FRC	14.42 MNm^{-2} [op]	3.00	70
		Cast post and core	16.24 MNm^{-2} [o]	2.60	10
		Prefabricated metal	13.00 MNm^{-2} [p]	2.53	10
Mannocci et al[16]	10	Carbon-quartz FRC	‡[q]	‡	‡
		Quartz FRC	‡[q]	‡	‡
		Ceramic	‡[r]	‡	‡
Studies without crown coverage					
Dean et al[8]	10	Carbon FRC	1,053.23 N[s]	257.91	100
		Prefabricated metal	1,094.42 N[s]	186.33	50
		Prefabricated metal	1,057.16 N[s]	171.62	50
Stockton and Williams[17]	13	Carbon FRC	208.88 N[t]	72.47	100
		Carbon FRC	253.01 N[t]	62.27	92
		Prefabricated metal	232.42 N[t]	67.67	100
Cormier et al[13]	10	Carbon-quartz FRC	176.10 N[u]	22.70	70
		Carbon FRC	183.30 N[u]	10.40	60
		Glass FRC	108.60 N[v]	6.30	100
		Ceramic	179.70 N[u]	10.60	70
		Cast post and core	184.80 N[u]	11.50	10
		Prefabricated metal	204.10 N[u]	10.60	40
Maccari et al[18]	10	Carbon-quartz FRC	818.86 N[w]	261.84	90
		Glass FRC	840.43 N[w]	173.58	100
		Ceramic	357.94 N[x]	162.79	70

*The same superscripted character within one study indicates mean failure load values that were not significantly different ($P > .05$).
†Failure mode not described.
‡Not all specimens failed. Mannocci et al[16] used cyclic loading; failures were expressed in No. of load cycles before failure. They found a significantly higher survival rate for FRC posts compared to the ceramic group (Kaplan-Meier).
FRC = fiber-reinforced composite.

Results

The MEDLINE literature search resulted in a list of 1,984 hits. After the first selection step, 244 articles remained; 1,740 were excluded. Complete agreement was seen for 1,923 papers, and consensus was reached in 61 cases (inter-reader agreement $\kappa = .86 \pm .02$).

The second step revealed 42 papers[1–3,6,8,11–47] related to fiber post systems (inter-reader agreement $\kappa = .99 \pm .01$). The hand search revealed 20 not-yet-identified references; however, these were excluded from further analysis with 100% agreement between the readers. Thirty papers were excluded in step 3 (Table 2). Twelve papers met the inclusion criteria (inter-reader agreement $\kappa = .68 \pm .12$), and their extracted data are depicted in Table 3.

The multinomial analysis of ∂FL scores revealed no significant difference for prefabricated FRC posts

Table 4 Reported Differences in Mean Failure Loads (∂FL) Within Studies and Level of Significance of Overall Effect

Comparison	∂FL = +1	∂FL = 0	∂FL = –1	N	*P* value
FRC–cast	0	8	4	12	.04
FRC–prefabricated metal	2	12	2	16	.15
FRC–ceramic	5	7	1	13	.02

∂FL = +1: mean failure load for FRC posts was significantly higher than that of compared post system; ∂FL = 0: no significant difference observed; ∂FL = –1: mean failure load for FRC posts was significantly lower than that of compared post system; N: No. of groups compared; FRC: fiber-reinforced composite.

compared to prefabricated metal posts (Table 4), which indicates that the reported failure loads were similar. On the other hand, positive ∂FL scores were found significantly more frequently for prefabricated FRC posts compared to ceramic post systems, indicating higher mean failure loads for FRC posts. In comparison to cast posts, ∂FL scores were significantly more often negative, indicating lower mean failure loads for prefabricated FRC posts (Table 4).

The failure modes as described in the articles were dichotomized, with inter-reader agreements of $\kappa = .99 \pm .01$ for FRC posts and $\kappa = 1.00$ for the other post systems. The Wilcoxon signed ranks tests showed significantly higher percentages of favorable failures in the prefabricated FRC post groups than in the prefabricated metal post groups (number of pairwise comparisons = 16, $P = .013$, $z = 2.49$) and cast post groups (n = 11, $P = .005$, $z = 2.82$). No significant difference was found between failure modes of prefabricated FRC post systems and ceramic post systems (n = 11, $P = .560$, $z = 0.59$).

Discussion

A structured analysis of the relevant scientific literature is a state-of-the-art method of summarizing the increasing amount of information on specific topics in (dental) research.[48] The method used in systematic reviews, which were originally designed for inference of randomized clinical trial outcomes, is well-suited to analyzing results of in vitro studies on post-and-core systems. The present review followed the structure of a systematic review, except for the phase of quality control of included papers.[49] Criteria for quality control of randomized controlled clinical trials and other types of clinical studies have been described extensively.[49–54] These criteria are hardly applicable to the current data, and international consensus would be minimal. We consider the present blinded review as systematic, reproducible, and covering the relevant current literature. It was not intended to cover the gray literature (information not reported in periodic scientific literature[9]) or papers in languages other than English.

The selection procedure started with a broad search strategy. This step could have been more focused by adding specific search terms such as fibre* or fiber*. However, we would not take the risk of excluding new post systems if they were described as polymeric. The use of only one data source (MEDLINE) carries a chance of selection bias. To overcome this problem, the reference lists of included articles were hand searched. Since no additional papers that met the inclusion criteria were found, it was considered unnecessary to apply other databases. The inter-reader agreements were unusually high, probably as a result of the criteria that allowed obvious exclusions.

All selected articles except one[16] describe failure loads and failure modes resulting from static load testing of restored single-rooted teeth embedded in acrylic or resin with[6,16] or without[1,2,8,11–15,17,18] an artificial periodontal ligament. The studied specimens were heterogeneous on several aspects as well, which hampers direct comparability of the results. For example, the height of the reduced clinical crown varied from 0 mm[6,11,13] to 4 mm[14] as measured above the cementoenamel junction, while other studies standardized the root length.[8,16,18] The ferrule, regarded as an important factor in fracture resistance and failure mode of crowned teeth with post-and-core restorations, varied from 1 mm[1,2,11–13,15] to 2 mm.[15] Three papers studied post-and-core restorations without covering crowns,[13,17,18] and one study tested crown-prepared post-and-core buildups without crowns placed.[8] Furthermore, heterogeneity was caused by variation in length and diameter of posts, post brand, and type of tooth (incisors, canines, or premolars).

Besides the above-described factors, test design also contributes to a wide range of failure loads and hinders direct pooling of the results. For instance, one study simulated the worst-case scenario of force application to a restoration, with a 90-degree angle of incidence between the compressive head of the universal testing machine and the long axis of the tooth specimen.[13] This can be the cause of low forces to failure compared with studies using a loading angle of 130 to 135 degrees. Two studies recorded relatively high failure loads.[1,8] Possibly, those studies recorded the peak load at failure (final failure) instead of the first drop of the load (initial failure), the latter being recorded at lower loading levels.[11,12] Dean et al[8] state that their high failure loads were due to the low load rate used (0.5 mm/min).

Despite the heterogeneity in specimen and study designs, we were able to compare the results of different studies by using a multinomial statistical technique. This technique allows determination of overall statistical significance of the measured effects by comparing the direction of significant differences in mean failure loads of post systems within each study. The failure mode comparison revealed less-frequent dramatic failures for prefabricated FRC posts and cores than for metal post systems. This feature is often explained by the higher rigidity of metal posts. It has been suggested that FRC posts show reduced stress transmission to the root because of isoelasticity compared to dentin (E-modulus of FRC posts = 9 to 50 GPa; dentin = 14 to 18 GPa[13,18,55]). It should be noted that, in addition to the importance of the E-modulus of the post for the restoration's strength, the load-bearing capacity of the post must also be considered. In this context, the diameter of the post is of importance. For instance, a 1.4-mm-diameter carbon/graphite post has a load-bearing capacity of 85 N, whereas a 2.1-mm-diameter post has a capacity of 200 N.[55] The increased load-bearing capacity of thicker FRC posts obviously increases the rigidity of the post construction, which can overrule the E-modulus, a material property. Thus, it is possible that FRC posts can produce similar types of failures as ceramic posts with even higher stiffness (E-modulus of ceramic posts = 170 to 213 GPa[13,18]). This has also been found in the present study.

Although ceramic posts of zirconium oxide are strong compared to prefabricated metal and carbon FRC posts, they are reputed to have low resistance to crack propagation.[56] Failures of the ceramic post–tooth complex in the selected studies were predominantly fractures of the posts, without root fractures.[6,12,13,16,18] Possibly, the fracture of the ceramic post absorbed most of the energy, thereby saving the remaining root from fracture. Some authors interpret the fracture of a ceramic post to be a disadvantage, since fractured ceramic posts are difficult to retrieve from the root canal in clinical situations.[13,56] It has been suggested that crown-covered posts and cores are more fracture resistant but tend to show more irreparable failures.[9] Although not part of the present analysis, the data expressed in Table 3 seem to underline this suggestion.

FRC post systems are now placed routinely in patients. This practice is based only on theoretic knowledge of the material properties and laboratory experiments rather than on clinical data, since prospective clinical studies are not yet available. The present review attempts to present the current knowledge regarding in vitro failure loads and failure modes of prefabricated FRC post systems in comparison to other systems. One should be cautious in extrapolating the conclusions directly into the clinical situation because test conditions did not resemble reality. For example, static loading tests do not represent masticatory function. So far, only a few investigators[3,4,16] attempted to approach the in vivo situation more closely by using fatigue tests.

From the fracture resistance point of view, one could prefer custom-cast posts to prefabricated FRC posts for restoring single-rooted teeth, but prefabricated FRC posts to ceramic posts. However, these pooled data revealed significantly more favorable failures for prefabricated FRC post systems compared to prefabricated metal and custom-cast post systems. It should be emphasized that a more favorable failure mode could be more valuable than a high fracture resistance. Further research, including fundamental investigation of the role of the design and rigidity of post-and-core construction and the influence of the adhesive interfaces between the materials, is needed.

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