A NOVEL MOLDLESS SINTERING POROUS TITANIUM FOR DENTAL POST SYSTEM: DEVELOPMENT, CHARACTERIZATION AND EVALUATION OF MECHANICAL PROPERTIES

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by

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LIST OF ABBREVIATIONS

Pt-Au-Pd	Platinum-gold-palladium
Ni-Cr	Nickel-chromium
Co-Cr	Cobalt-chromium
CEJ	Cemento-enamel-junction
N	Nitrogen
C	Carbon
O	Oxygen
FESEM	Field-emission scanning electron microscopy
EDX	Energy dispersive X-ray spectrometry
PTP	Porous titanium post
CTP	Commercially-pure titanium post
SSP	Stainless steel post
FGP	Fiber glass post
FRP	Fiber reinforced post
MPa	Mega Pascal
CI	Confidence interval
PBS	Push-out bond strength
SD	Standard deviation
ANOVA	Analysis of variance
ISO	International Organization for Standardization
USM	Universiti Sains Malaysia

LIST OF APPENDICES

PENSINTERAN TITANIUM BERLIANG TAK BERACUAN TERBAHARU UNTUK SISTEM TIANG PERGIGIAN: PEMBANGUNAN, PERCIRIAN DAN PENILAIAN SIFAT MEKANIKAL

ABSTRAK

Pelbagai jenis tiang intraradikular telah tersedia dalam rawatan pemulihan gigi yang dirawat secara endodontik. Walau bagaimanapun, nyahikatan tiang masih menjadi kelemahan utama sehingga kini. Dalam kajian ini, kami telah membangunkan tiang pergigian titanium berliang untuk meningkatkan fleksibiliti tiang, dan dengan permukaan berliang untuk menambah baik “interlocking” mikro dengan simen luting. Pada bahagian pertama, serbuk titanium tulen telah dicampur dengan pengikat lilin (sebagai pemegang ruang) dalam tiga peratusan yang berbeza (85%, 90%, dan 95% berat serbuk titanium). Sampel-sampel tersebut telah didedahkan pada suhu pemanasan dalam dua fasa. Dalam fasa pertama (pemanasan udara), sampel-sampel telah dipanaskan dalam persekitaran terbuka selama 2 jam (pada suhu 380◦C) untuk menyingkirkan pengikat lilin. Dalam fasa kedua, sampel-sampel tersebut kemudiannya telah disinter di dalam relau tiub dengan persekitaran argon selama 10 jam (pada 1100◦C) untuk melengkapkan proses. Sampel-sampel kemudiannya dicirikan dan diuji untuk memilih campuran yang terbaik untuk penyiasatan lanjut. Pancaran medan pengimbasan elektron pengimbasan (FESEM) menunjukkan kekasaran permukaan yang baik dan keliangan pada keseluruhan struktur, dengan peleburan zarah titanium yang lebih baik dalam kumpulan 85%. Analisis penyebaran tenaga spektrometri sinar-X (EDX) menunjukkan peratusan titanium yang lebih tinggi di dalam bahan. Nilai ketumpatan adalah hampir dengan nilai teori, dan keliangan menunjukkan taburan yang baik dengan kurang daripada separuh daripada isi padu (40%). Ujian kekuatan mampatan dan lenturan menunjukkan nilai kumpulan 85%

adalah lebih tinggi berbanding kumpulan lain. Kumpulan 85% kemudiannya telah dipilih untuk dijadikan tiang titanium berliang (PTP). Pada bahagian kedua, 96 gigi manusia telah dikumpulkan untuk menyiasat kekuatan ikatan penolakan tiang berliang. Dua simen luting berbeza (RelyX U200™ 3M ESPE dan ParaCore® Coltene Whaledent) telah digunakan dan akar gigi dipotong pada bahagian koronal dan aras tengah (dengan ketebalan 3.00 ± 0.2 mm). Kekuatan ikatan penolakan PTP telah dibandingkan dengan tiang pergigian lain (Coltene Whaledent) iaitu: tiang titanium tulen komersial (CTP) (ParaPost® XP), tiang keluli tahan karat (SSP) (ParaPost® XP), dan tiang gentian fiber (FGP).) (ParaPost® Fiber Lux). Nilai kekuatan ikatan penolakan PTP adalah setanding dengan tiang-tiang lain, tanpa perbezaan yang signifikan (P> 0.05) dalam kumpulan RelyX U200 pada kedua-dua bahagian aras akar gigi. Lekatan PTP adalah lebih baik daripada tiang-tiang lain, tanpa prevalens kegagalan selepas disimen pada PTP. Imej FESEM pada antara muka tiang-simen-dentin menunjukkan lekatan PTP yang lebih baik pada kedua-dua jenis simen, tanpa garis pemisah yang jelas kelihatan antara tiang dan simen. Dapatan kajian ini memberi kemungkinan untuk penggunaan tiang titanium berliang sebagai pilihan alternatif untuk sistem tiang pergigian.

A NOVEL MOLDLESS SINTERING POROUS TITANIUM FOR DENTAL POST SYSTEM: DEVELOPMENT, CHARACTERIZATION AND EVALUATION OF MECHANICAL PROPERTIES

ABSTRACT

Different types of intraradicular posts are available to restore the endodontically-treated teeth. However, debonding of the post is still the main drawback till date. In this study, we developed a porous titanium dental post with porosity to increase the flexibility of the post, and with porous surface to improve the micro-interlocking with the luting cement. In the first part, pure titanium powder was mixed with wax binder (as space holder) in three different percentages (85%, 90%, and 95% wt. titanium powder). The samples were exposed to heating temperature through two phases. In the first phase (air heating), the samples were heated in an open-air environment for 2 hours (at 380◦C) to remove the wax binder. In the second phase, the samples were sintered in a tube furnace with argon environment for 10 hours (at 1100◦C) to complete the process. The samples were then characterized and tested to select the best mixture for further investigation. The field-emission scanning electron microscopy (FESEM) showed good roughness of the surface and thorough porosity of the structure, with better melting of the titanium particles in the 85% group. The energy dispersive X- ray spectrometry (EDX) analysis showed higher percentages of titanium within the material. The density values were close to the theoretical ones, and the porosity revealed good distribution with less than half of the volume (40%). The compressive and flexural strength tests revealed higher values of 85% group than other groups. The 85% group was then selected to fabricate the porous titanium post (PTP). In the second part, 96 extracted human teeth were collected to investigate the push-out bond strength of the porous post. Two different luting cements (RelyX U200™ 3M

ESPE and ParaCore® Coltene Whaledent) were used and the roots were sectioned at the coronal and middle levels (3.00 ± 0.2 mm thickness). The push-out bond strength of the PTP was compared to other dental posts (Coltene Whaledent) namely commercially-pure titanium post (CTP) (ParaPost® XP), stainless steel post (SSP) (ParaPost® XP), and fiber glass post (FGP) (ParaPost® Fiber Lux). The push-out bond strength values of PTP were comparable to that of the other posts, with no significant differences ($P > 0.05$) in RelyX U200 group at both sections of the root. The adhesion of PTP was better than the other posts, with no prevalence of post-cement failure in PTP. FESEM images on the post-cement-dentin interface showed better adhesion of PTP to both types of cements, with no visible separating line between post and cement. The findings of this study provide a possibility to use the porous titanium post as alternative option for dental post systems.

CHAPTER 1

INTRODUCTION

1.1 Background

Pulpless teeth can still survive for long time if they are properly treated. The restoration of such teeth can be done by the replacement of the missing structures. Such restorations need some source of support which can be achieved from the root canal by using intraradicular post (Fernandes & Dessai, 2001; Torbjörner & Fransson, 2004; Bitter & Kielbassa, 2007; Biabani-Sarand *et al.*, 2022). Varieties of endodontic posts are available for the dental practitioner to support the build-up core of the endodontically-treated teeth. These endodontic posts can be fabricated in the dental laboratory using metal by cast method or can be ready-made (prefabricated), which are made of different types of materials such as metal, fiber-reinforced resin, and ceramic (Bolla *et al.*, 2016; Machado *et al.*, 2017).

Among the popular non-metal posts used, the fiber post-and-core system has been extensively investigated and supported by clinical and laboratory studies (Smith & Schuman, 1998; Teixeira *et al.*, 2006; Theodosopoulou & Chochlidakis, 2009; de Moraes *et al.*, 2013; Gbadebo *et al.*, 2013, 2014; Sonkesriya *et al.*, 2015; Thakur & Ramarao, 2019; Mayya *et al.*, 2020; Martins *et al.*, 2021). A comprehensive understanding of the characteristic of post material and the particular condition of root canal dentin in the post space will help to improve this material for longer adhesion with the cemented restoration (Goracci & Ferrari, 2011; Machado *et al.*, 2017). The non-metal post had been developed due to advanced technology in biomaterials systems, development of adhesive systems, and enhancement of aesthetic characteristics of dental restorations (Stewardson, 2001). This type of dental posts has elastic modulus close to that of dentin which makes it more flexible than metallic posts (Plotino *et al.*, 2007; Hu *et al.*, 2012; Gallicchio *et al.*, 2022). When compared to other esthetic non-metallic post (zirconium), teeth restored with fiber glass posts showed higher values of fracture resistance and more prevalence of desirable failure modes (Habibzadeh *et al.*, 2017). However, some drawbacks are still associated with this type of posts such as debonding of the posts, a problem still encountered in the dental practice (de Moraes *et al.*, 2013).

Among the metallic posts, titanium posts remain popular in the dental practice. Titanium is a good biocompatible material and has excellent properties such as good corrosion resistance, low density, low thermal conductivity, low weight, and low cost. Moreover, it can be easily prepared and machined in many different shapes and textures without the loss of its biocompatibility properties (Branemark, 1983; Kasemo & Lausmaa, 1988; Sommer *et al.*, 2020). With regards to fracture resistance, many studies found no significant differences in fracture resistance between both types of post namely non-metallic and metallic posts (Alhajj *et al.*, 2021; Iaculli *et al.*, 2021; Silva *et al.*, 2021).

Recently, porous titanium has been used in many medical and dental disciplines such as orthopaedic and dental implant systems (Spoerke *et al.*, 2005; de Vasconcellos *et al.*, 2008; Naito *et al.*, 2013; Palka & Pokrowiecki, 2018; Llopis-Grimalt *et al.*, 2020). The porous titanium implant was developed by Dr. Naito and tested in animal studies (Alenezi *et al.*, 2013; Naito *et al.*, 2013; Prananingrum *et al.*, 2016). The presence of porosity on the surface of the implant will enhance the osseointegration. There are no data available on porous titanium post; since this will be the new category of post systems. This study, therefore, aimed to fabricate a new titanium porous post, analyse its characterizations and mechanical properties in terms of the compressive and flexural strengths, and to compare the bonding strength with other types of posts cemented with two types of dual-cure resin cement and tested at two levels of the root.

1.2 Problem statements

Various endodontic posts are available to restore and stabilize the endodontically-treated teeth. Some types of the dental posts are active posts which retain to the root dentin through mechanical interlocking via post threads. However, this type of interlocking can cause more stress on the dentin leading to root fracture. Other types of posts are passive posts which requires luting cement to retain them to the root dentin. One drawback of dental posts, namely titanium posts, is the non-matched elastic modulus between titanium dental post and root dentin (Bolla *et al.*, 2016; Machado *et al.*, 2017).

Hence, aesthetic posts remain popular particularly with the development of fiber post due to some features like tooth matching colour and desirable elastic modulus similar to dentin. Debonding of the post remains a problem causing failure of the restoration and consequently failure of the endodontic treatment (de Moraes *et al.*, 2013). Moreover, the prefabricated dental posts might fit poorly inside the root canal, particularly with flared and large root canals. Thus, the presence of a large gap between root dentin and post means thicker layer of luting cement, which in turns will negatively affect the bonding of the post (Caneppele *et al.*, 2010; Farid *et al.*, 2018).

The development of this new titanium porous is an attempt to overcome the stiffness of the current metal post which can cause fracture of the tooth by improving the flexural strength to simulate the strength of the dentin thus, enhancing the resistance of the endodontically-treated teeth retained tooth with post during flexion. Another reason is to improve the bonding between the post and the dentin by providing a porous surface with this new titanium post.

Many different factors that will affect the bond strength of cemented post inside the root canal may need to be considered; one of these factors is the post surface. The research will help to understand the new properties of the porous titanium post system and improve their clinical performance. The literature is limited regarding the differences in dual-cure resin cement bond strength among the newly developed porous titanium posts.

1.3 Justifications of the study

This study will investigate the possibility of developing a new type of dental post system; that is a porous titanium dental post system. Even with the fast emerging of the fiber post, the metal post still has its place especially with the posterior teeth where aesthetic is less of a concern but the teeth are still heavily subjected to the mastication force. By introducing a more flexible post similar dentin, it is hoped that the incidence of fractured tooth which often irreparable due to the stiffness of the current metal post can be reduced.

The study will contribute useful information regarding the improvement of bonding between post and luting cements. Characteristics of the porous titanium post surface may show significantly higher bond strength with the luting cement.

Modification of the post surface can significantly improve the bonding without actively engage to the tooth structure, a problem that can lead to root fracture.

This project will help the dentist to select the better, as this new porous titanium post may be more flexible than the commercially-pure titanium post. Moreover, the porosity will lead to less grey color for porous titanium post. Still, the possible strength is higher than fiber post; but justifies developing this new type of post due to the significant clinical use. This new porous titanium post could be investigated for further use in clinical dentistry as one of the new alternatives in post systems.

1.4 Research questions

Considering that there is no data available in the literature about the newly developed titanium porous regarding the flexural and compressive strength and the differences in the bond strength of dual-cure resin cement among different types of posts, these are the questions raised.

1. Is it possible to develop a porous titanium using the moldless technique with satisfactory characterizations and mechanical properties?

2. What is the most appropriate percentage for mixing titanium powder and wax binder for optimal results of titanium porous post?

3. Is there any significant difference in the push-out bond strength of porous titanium post compared to other types of dental posts when luted with two different types of cements at two levels of the root?

4. Is there any significant difference in the failure pattern of the porous titanium

post compared to other types of dental posts when luted with two different types of cements at two levels of the root?

5. Is there any microscopic difference on the porous titanium surface at post-cement-dentin interface?

1.5 Research hypotheses

1. There is a possibility to fabricate and characterize a new porous titanium post using the new moldless technique.

2. There is no significant difference in mechanical properties between different groups of titanium porous.

3. There is no significant difference in the push-out bond strength between porous titanium post and commercially available posts (metal and fiber posts) when luted with two different types of cements at two levels of the root.

4. There is no significant difference in pattern of failure between the porous titanium post and commercially available posts (metal and fiber posts) when luted with two different types of cements at two levels of the root.

5. There is no difference in microscopic analysis of post-cement-dentin interface between porous titanium post and commercially available posts (metal and fiber posts).

1.6 Objectives of the study

1.6.1 General objectives

To develop a new porous titanium and to analyze its characterizations and mechanical properties in terms of compressive and flexural strengths, and to compare the push-out bond strength of this new post with other different types of dental post.

1.6.2 Specific objectives

1. To fabricate a new type of porous titanium post and evaluate its characterizations using field-emission scanning electron microscope (FESEM), energy-dispersive X-ray spectroscopy (EDX analysis), density, and porosity.

2. To analyze the compressive and flexural strengths of the new fabricated titanium porous samples with different percentages (85%, 90%, and 95%) in order to select the most appropriate mixture for the fabrication of the titanium porous post.

3. To compare the push-out bond strength between the new porous titanium post with commercially-pure titanium post, fiber glass post, and stainless steel post cemented with two types of dual-cure resin cement, RelyX U200® (3M ESPE) and ParaCore® (Coltene Whaledent) at the coronal and middle levels of the root.

4. To compare the failure pattern of the tested posts at the interface level (adhesion or cohesion) of porous titanium, metal, and fiber posts cemented

with two types of dual-cure resin cement, RelyX U200® (3M ESPE) and ParaCore® (Coltene Whaledent) at the coronal and middle levels of the root.

5. To analyze the post-cement-dentin interface using FESEM of porous titanium, metal and fiber posts.

CHAPTER 2

LITERATURE REVIEW

2.1 Restoration of endodontically treated teeth

Following a successful treatment of the root canal system, the tooth can remain as functional unit within the dental arch by providing adequately support for the coronal tooth structure (Freno, 1998; Morgano *et al.*, 2004; Tait *et al.*, 2005; Fathi *et al.*, 2022). The design of the definitive restoration depends on the amount of the remaining tooth structure, the anatomical position of the tooth, the functional load on the tooth, and the aesthetic requirement. Treatment with definitive restoration in endodontically-treated teeth usually requires dental post for support especially when the remaining tooth structure is not enough to provide adequate retention and resistance form for final restoration (Freno, 1998; Fernandes *et al.*, 2003b; Musikant *et al.*, 2003; Bolla *et al.*, 2016).

The success of the restored endodontically-treated teeth depends on three factors: the root canal treatment, the post and core, and the coronal restoration. The factors influencing post selection are: root length, tooth anatomy, root width, canal configuration, amount of coronal tooth structure, torquing force, stresses, development of hydrostatic pressure, post design, post material, material compatibility, bonding capability, core retention, and esthetic (Fernandes *et al.*, 2003; Musikant *et al.*, 2003; Cheung, 2005).

Different types of tests have been used for assessing the bonding to root canal dentin: the tensile bond strength test, the push-out test, and the push-in test (nowadays less favoured). The microtensile bond strength test can be used with large numbers of small beam-shaped specimens, but standard deviation values and premature failure rates may be high (fracture of the samples before testing) for both trimmed and non-trimmed specimens (Pashley *et al.*, 1999; Goracci *et al.*, 2004; Pongprueksa *et al.*, 2016). The push-out test provides a better estimation of the bonding strength than the conventional shear test, because with the push-out test the fracture occurs parallel to the dentin-bonding interface, which makes it a true shear test (Pashley *et al.*, 1995; Sudsangiam & van Noort, 1999). Moreover, the push-out test simulates the clinical conditions more closely (Balbosh *et al.*, 2005).

2.2 Post system

The construction of posts has been used as means of providing anchorage for restorations for over 250 years ago with the placement of metal screw posts in the roots of teeth to retain prostheses. The primary purpose of a post is to retain the coronal restoration in an endodontically treated tooth that has suffered an extensive loss of crown structure (Schwartz & Robbins, 2004). Based on article by Fernandes, the factors influencing post selection are root length, tooth anatomy, root width, canal configuration, amount of coronal tooth structure, torquing force, stresses, development of hydrostatic pressure, post design, post material, material compatibility, bonding capability, core retention, irretrievability, esthetic, and crown material (Fernandes *et al.*, 2003).

2.2.1 Ideal properties and features of an endodontic post

Dental posts should have as many of the following properties/features as possible (Fernandes *et al.*, 2003; Trushkowsky, 2008; Dikbas & Tanalp, 2013; Wang *et al.*, 2019):

- Provide maximum retention and core stability.
- Compatible to the dental tissue.
- Require minimal removal of dental tissue.
- Has a shape similar or close to the canal morphology.
- Fulfil accurate adaptation with the root canal.
- Uniform distribution of the functional stresses along the root canal.
- Optimal esthetic compatibility with restoration and dental tissue.
- Exhibits minimal stresses during insertion and cementation.
- Resistance to dislodgement and displacement.
- Has modulus of elasticity, and flexural and tensile strengths similar to root dentin.
- Easy to be retrieved in case of re-treatment.
- Made of material that are compatible with the cores and/or bonding systems.
- Has anti-rotation shape/design.

- Ease of use, safe with no harmful effects.
- Affordable cost.

2.2.2 Types of dental posts

There are different types of dental post system either custom-made post or prefabricated post (Schwartz & Robbins, 2004; Sahafi & Peutzfeldt, 2009; Goracci, & Ferrari, 2011; Machado *et al.*, 2017; Jafari *et al.*, 2021). Prefabricated posts are constructed from different materials such as metal, ceramic, zirconia, polyethylene and fiber reinforced composite material (Figure 2.1)

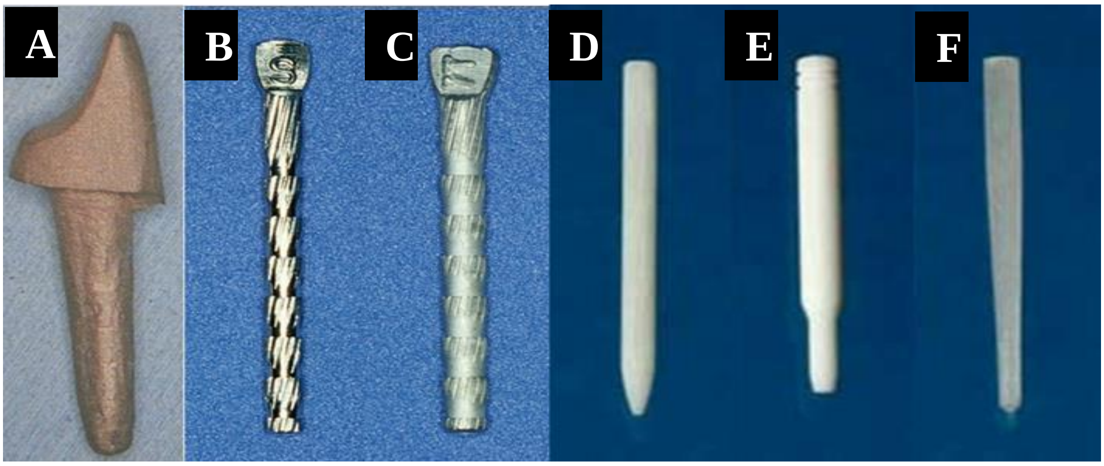

Figure 2.1 Different types of dental post: From left to right; A) Metallic cast dental post and core, B) Stainless steel dental post, C) Titanium alloy dental post, D) All-ceramic dental post (alumina), E) Zirconia dental post, and F) Glass fiber dental post (adapted from Schwartz & Robbins 2004; Sahafi & Peutzfeldt 2009).

2.2.2(a) Custom-made metal posts

Due to their superior physical properties, custom-made posts became a marked treatment option (Creugers *et al.*, 1993; Morgano, 1996; Awad & Marghalani, 2007). Preparation of such posts should be slightly tapered with no undercuts to ease the withdrawal of the impression, insertion of the post, and even retrieval of the post (Baraban, 1988). Different materials can be used for fabrication of these posts such as: gold alloys, silver-palladium alloy, base-metal alloy, and other non-precious alloys (Robbins, 1990; Druttman, 2000; Mannocci & Cowie, 2014). They are fabricated directly or indirectly and used mainly in teeth with large root canals. Their main drawbacks are that they need special equipment for fabrication, multiple appointments, temporization, and a laboratory fee.

For many years, custom-made post and cores were the treatment of choice and are still used by some clinicians today. However, they do not perform superior when compared to the other types of posts during in-vitro experiments (Isidor & Brøndum, 1992; Isidor *et al.*, 1996) and clinical studies (Morgano & Milot, 1993; Torbjörner *et al.*, 1995). On the other hand, some studies reported high rate of success with custom-made post and cores, and they offer advantages in certain clinical situations (Weine *et al.*, 1991; Balkenhol *et al.*, 2007; Salvi *et al.*, 2007; Eliyas *et al.*, 2015; Martino *et al.*, 2020; Fathi *et al.*, 2022). Well-fitting and well-adapting custom-made posts are needed to resist the torsional forces. One superior advantage of the custom-made post and core is that if a tooth is misaligned, the core can be angled in relation to the post to achieve proper alignment within the dental arch. A custom-made post and core may also be indicated when there is minimal coronal tooth structure available for anti-rotation features or bonding. Despite the above-mentioned features, cast posts have also their disadvantages. They have low retentive abilities and the technique is both time-consuming and expensive. Furthermore, a temporary restoration is also always required, increasing the risk of contamination of the root canal system (Naoum & Chandler, 2002; Fox & Gutteridge, 2003; Racanshad, 2003; Mohajerfar *et al.*, 2019). In addition, in certain cases, the need for more aesthetic solutions has launched the development of new alternative post materials.

The fabrication of custom-made metal posts can be done by two techniques/methods (direct and indirect). In the direct method, the preparation of the post space is done first and the fabrication of post pattern is followed directly in the patient's mouth at the dental clinic using the appropriate materials such as wax or acrylic. After that, the post pattern is sent to the dental laboratory to proceed with the next steps including spruing, investing, burn-out, casting and then sending it back to the clinic for cementation. In the indirect method, however, the preparation of the post space is done first as in the direct method but no fabrication of the post pattern is done in the clinic. Rather, the dental practitioner takes an impression for the post space using specific materials for this such as polyvinyl siloxane and then sends the impression to the dental laboratory. In the dental laboratory the technician pours the impression to get the dental die model that represents the root and root canal. In this model the dental technician starts fabricating the post pattern and then completes the procedures as mentioned in the direct technique (Hochstedler *et al.*, 1996; Zalkind & Hochman, 1998; Fokkinga *et al.*, 2004; Morgano *et al.*, 2004; Deger *et al.*, 2005; Sonkesriya *et al.*, 2015).

2.2.2(b) Prefabricated posts

2.2.1(b)(i) Metal posts

This metal post can be made from platinum-gold-palladium (Pt-Au-Pd), nickel-chromium (Ni-Cr), cobalt-chromium (Co-Cr), or stainless steel wire. Titanium alloy has been commonly used for fixed restoration including the post because of its excellent biocompatibility and physical properties, such as low density, high mechanical strength, and high corrosion resistance (Schmitter *et al.*, 2007). A recent randomized clinical trial compared the clinical survival rate between metal screw post restoration and fiber reinforced post (FRP) restoration reported that, for two-years survival rate of FRP was 93.5 %, while that of metal screw post was 75.65 %, showing a significant difference between the survival rates. In addition, fiber reinforced post failures occurred due to the debonding of the post, fracture of the crown or presence of apical lesions, metal screw post failure were associated with more unfavourable complication such as root fracture (Schmitter *et al.*, 2007).

Metallic prefabricated posts are made mostly of stainless steel or titanium alloys. The most common stainless steel used in prefabricated posts contains 18 percent chromium and only 8 percent nickel (Anusavice, 2003). However, because of the potential allergy of stainless steel posts, the risk of corrosion, and the high risk of root fracture, titanium posts were introduced (Silness *et al.*, 1979; Sorensen *et al.*, 1990; Dionysopoulos *et al.*, 1995; Plotino *et al.*, 2007). Compared to cast gold, titanium, and carbon fiber posts, metal posts had higher fracture resistances (Isidor *et al.*, 1996). Higher retention with stainless steel than carbon fiber posts when both were cemented with resin luting cement was also reported (Purton *et al.*, 2000). However, no difference in shear strength was found among stainless steel and three commercial brands of fiber posts cemented with the same resin luting agent (Drummond, 2000). Cormier *et al.* (2001) investigated the fracture resistance of gold, stainless steel, and four commercial brands of fiber posts and reported that teeth restored with stainless steel posts had the highest fracture resistance, whilst teeth restored with one of the quartz fiber post systems had the lowest. Newman *et al.* (2003) compared the fracture resistance of stainless steel posts with three brands of fiber posts and found higher fracture resistance in teeth restored with the stainless steel posts.

2.2.1(b)(ii) Ceramic posts

The unpleasant display of the metallic posts has reduced their use in today dental practice and led to the introduction of more translucent all-ceramic restorations. Even with less translucent restorations metal posts may cause the marginal gingiva to appear darkish. Zirconium and other ceramic materials are used to achieve aesthetic appearance for posts. Although zirconia posts offer some advantages with respect to aesthetics and biocompatibility (Purton *et al.*, 2000), they have several disadvantages such as rigidity as well as brittleness (Asmussen *et al.*, 1999; Hedlund *et al.*, 2003; Alqutaibi *et al.*, 2022). Therefore, a deep preparation of the root canal is mandatory when using zirconia posts. Poor resin bonding capabilities of the zirconia posts to radicular dentine after dynamic loading and thermocycling (Dietschi *et al.*, 1997, 2006). However, in another study, Purton *et al.* (2000) found that the zirconia posts exhibited lower retention values than serrated metal posts. On the other hand, Paul & Werder (2004) observed good clinical success of zirconia posts with direct composite cores after few years of clinical service (a mean of 4.7 years).

2.2.1(b)(iii) Fiber-reinforced composite posts

Fiber posts can be considered as composite reinforced materials where fibers are embedded in a matrix of epoxy-resin or methacrylate-resin (Elsubeihi *et al.*, 2020). These materials are linked together using an interfacial agent such as silane. The post is fabricated through a technique called pultrusion which is a semi-automated industrial process (Mahesh *et al.*, 2021). The resinous matrix (epoxy or methacrylate) is injected into the pre-tensioned fiber bundle to completely fill the spaces between fibers (Shalwan & Yousif, 2013; Lamichhane *et al.*, 2014). Alternatively, fibers can be simply immersed in a resin bath. The diameter and density of the fibers as well as the adhesion between them and the matrix strictly influence the quality of the post and its mechanical properties. The quality, mechanical and clinical behaviour of posts are varied according to differences in the manufacturing processes (Grandini *et al.*, 2005).

For pleasant aesthetics appearance, especially when restoring anterior teeth to provide support for all-ceramic crowns, the translucent fibers (glass or quartz) were used as alternatives to dark fibers (Vichi *et al.*, 2000; Ferrari M, 2002). Moreover, the translucency of these fibers facilitates the polymerization process of the luting cement. The main advantage of fiber posts is the variability of their modulus of elasticity depending on the loading direction; in particular, during transversal loading, the modulus of elasticity has a value close to sound dentine (Ferrari M, 2002; Jawed *et al.*, 2022). This property reduces stress transmission to the root canal walls thus reduces the risk of vertical fractures (Asmussen *et al*., 1999). Debonding is the most common failure that can occur with a fiber post, especially during the removal of the temporary restoration. However, this failure can be dealt with by repeating the adhesive procedures (Cormier *et al.*, 2001). This type of failure may be due to the amount of tooth structure preserved compared to the tooth structure that must be removed when a metallic post is placed (Stankiewicz & Wilson, 2008; Juloski *et al.,* 2012). When failure occurs, some fractures called favourable fractures are seen in teeth restored with fiber posts and resin cores, whereas unfavourable fractures or failures are usually encountered with the use of a metal post (Heydecke *et al.*, 2002).

Fibers are oriented parallel to the post longitudinal axis and their diameter ranges between 6 μm and 15 μm. Nowadays, the restoration of endodontically treated teeth is based on the use of materials with a modulus of elasticity similar to that of dentin (18.6 GPa) as fiber posts and resin cements (Ferrari, 2002; Bitter & Kielbassa, 2007). The clinical effectiveness of such restorations has been mainly referred to the more biomimetic behavior of fiber-reinforced composite posts. Specifically, in the presence of the less rigid fiber posts, the placement of a fiber-reinforced composite post protects against failure, especially under conditions of extensive coronal destruction. The most common type of failure with fiber-reinforced composite posts is debonding (Goracci, & Ferrari, 2011). A study by Kivanç & Görgül (2008) about the fracture resistance of anterior teeth restored with three different type of post systems showed that endodontically-treated anterior teeth restored with glass fiber posts exhibited higher failure loads than teeth restored with zirconia and titanium posts.

2.3 Biomechanical properties

Restoration of endodontically compromised teeth using dental posts is usually indicated when there is a considerable destruction of the crown that is not sufficient to withstand and support a core post-free filling (Mannocci *et al.,* 1999; Mannocci & Cowie, 2014). These dental posts play essential role in the distribution of the stress to the surrounding and supporting dental tissues. Therefore, dental posts should be made of material that have biomechanical properties similar to that of dentin to permit a uniform distribution of the stress and to disseminate the forces to the surrounding dental tissue in order to prevent root fracture (Bonfante *et al.*, 2007; Kainose *et al.*, 2015). Figure 2.2 depicts the different directions of stress distribution when using different restoration systems comparing with the healthy teeth. It can be noted that Gutta-percha is the best intracanal filling material in disseminating the functional stress comparing with dental posts (Vishwanath & Rao, 2019). However, there is a need for stronger intracanal restoration (posts) to withstand the occlusal forces in case of restoration of teeth with considerable destruction.

One of the most important properties of the intracanal restorative material, from a mechanical and physical points of view, is that the material should be similar or close to dentin. Among all the available dental posts in the dental market, fiber-reinforced posts seem to have biomechanical properties approximately similar or close to that of dentin, particularly the elastic modulus (Dikbas & Tanalp, 2013). Resistance to fracture of the dental posts is determined by its flexural strength as well as its elasticity (elastic modulus) (Plotino *et al.*, 2007). It has been shown that the results of the 3-point flexural strength test revealed that fiber dental posts are about four times higher than dentin, while metal dental posts are about seven times higher than human dentin (Mannocci *et al.*, 2001). In fiber dental posts, some contents influence its flexibility such as the amount of impeded fiber and the amount of resin as well. Other factors include the diameter of the fiber and the presence of porosity within the matrix (Bolla *et al.*, 2016).

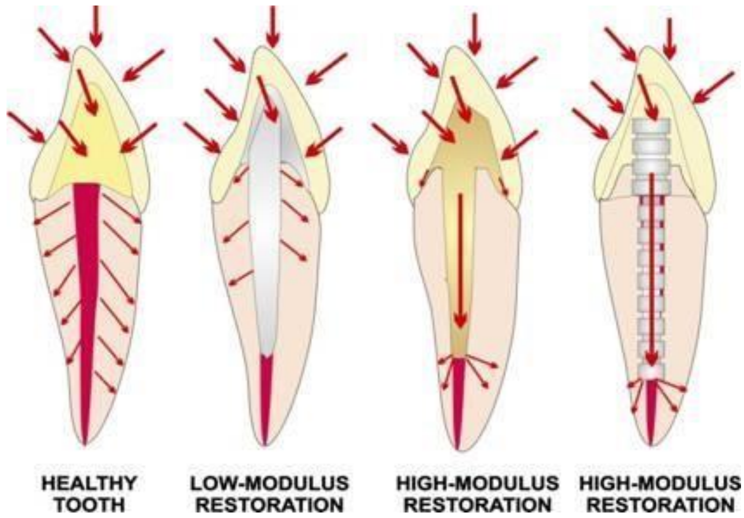

Figure 2.2 A schematic illustrating the function of intracanal post restoration stiffness on stresses distribution throughout the root of ETT. From left to right; healthy tooth, fiber dental post, cast metal dental post, and prefabricated metal dental post (adapted from http://www.rtd-dental.eu /GB/why post.php).

In addition to being compatible with the dental tissues, the clinical importance of the fiber dental posts rises from its low risk of root fracture. With the use of fiber dental posts, the fracture pattern, if happen, usually it occurs in the coronal portion of the root being restorable without deteriorating the integrity of the tooth (Santos *et al.*, 2010; Ona *et al.*, 2013). In contrast, the fracture pattern with cast dental posts is catastrophic and being un-restorable (usually appears as vertical fracture or at the apical portion of the root) (Saatian, 2006; Bijelic *et al.*, 2011; Sherfudhin *et al.*, 2011; Abduljabbar *et al.*, 2012; Bacchi *et al.*, 2019). Similarly, some in-vitro studies revealed that all ceramic (zirconium) dental posts have higher risk of root fracture when compared to fiber dental posts under fatigue loading (Hu *et al.*, 2003; Fokkinga *et al.*, 2006; Dayalan *et al.*, 2010; Habibzadeh *et al.*, 2017; Alkhatri *et al.*, 2019; Jafari *et al.*, 2021).

Another in-vitro study tested metal and fiber dental posts under similar cycling loads concluded that the length of the fiber dental post appears to be not important as it is for the metal dental post (Franco *et al.*, 2014). In contrast to this study, another study revealed that short fiber dental posts seem to disseminate more stress to the cervical area resulting in higher risk of cervical fracture (Jindal *et al.*, 2012). On the other hand, other factors rather than the post dimensions may influence the fracture resistance of the teeth; for example, the higher the ferrule the lower risk of fracture (Sorensen & Engelman, 1990b; Pereira *et al.*, 2009; Santana *et al.*, 2011).

Till date, no study could provide evidence-based conclusion that the dental posts can make the roots stronger and prevent root fractures (Dietschi *et al.*, 2008; Gluskin *et al.*, 2014; Liddelow & Carmichael, 2016). However, a clinical study by Guldener *et al.* (2017) investigated the of long-term outcomes of endodontically-treated teeth restored with fiber dental posts revealed higher success and survival rate compared to endodontically-treated teeth restored without the incorporation of dental posts. The authors also found that teeth restored with fiber dental posts exhibited low frequency of root fractures compared to teeth restored without dental posts.

In addition, some other clinical trial studies and systematic review concluded that fiber dental posts that have biomechanical properties close to dentin can improve the resistance to fracture of the endodontically-treated teeth, and showed lower incidence of catastrophic fracture modes when compared to metal dental posts (Schmitter *et al.*, 2011; Zhu *et al.*, 2015). On the other hand, some contradicted clinical studies showed no difference in performance of endodontically-treated teeth restored with metal/fiber dental posts compared with endodontically-treated teeth restored without dental posts (Jung *et al.*, 2007; Fokkinga *et al.*, 2008).

In summary, as the dental posts might enhance the endodontically-treated teeth and increase resistance to fracture, the preparation of root canal to receive the dental post might weaken it and makes it more susceptible to fracture and thus failure of the treatment. Therefore, the decision regarding using a supportive dental post should be made after a careful consideration of the remaining sound dental tissue particularly in the coronal portion, functional and occlusal loads, and esthetic requirements (Pilo, *et al.*, 2008; Jotkowitz & Samet, 2010). Figure 2.3 depicts the biomechanical criteria of some prefabricated posts (Smith *et al.*, 1998).

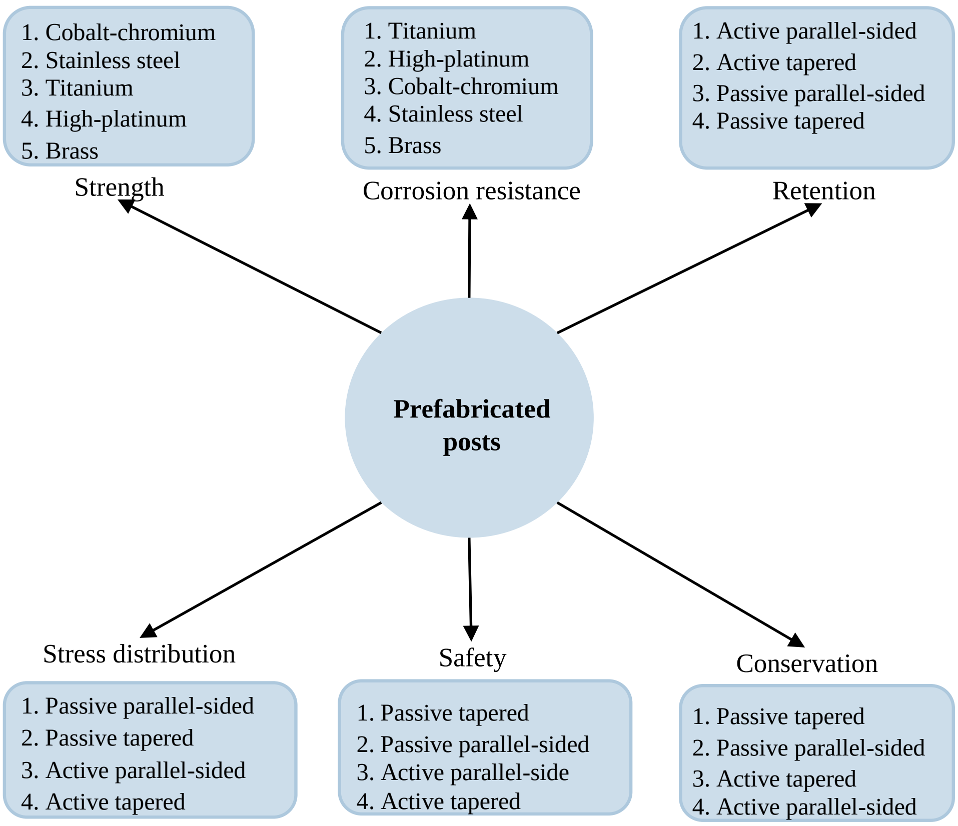

Figure 2.3 Biomechanical criteria of some prefabricated posts (adapted from Smith *et al.*, 1998).

2.4 Factors affecting post retention and fracture resistance

Retention of the post refers to its ability to resist the vertical forces without exhibiting any dislodgement. While the fracture resistance is the ability of the dental post to absorb or distribute the functional forces without cracking or breaking. There are several factors that can play a role in post retention and fracture resistance (Sorensen & Martinoff, 1984; Stockton, 1999; Fernandes & Dessai, 2001; Fernandes *et al.*, 2003; Fraiman, 2010; Skupien *et al.*, 2015); these factors could be summarized as following:

2.4.1 Post length

The dental literature is rich with recommendations regarding the appropriate post length. Some authors suggested that the post length should be equal to the length of the crown (inciso-cervical or occluso-cervical dimension) (Sheets, 1970; Harper & Lund, 1976; Stockton, 1999). Some others suggested that post length could be longer than the length of the crown (Silverstein, 1964; Peroz *et al.*, 2005); or it could be as long as possible without deteriorating the apical seal (Hirschfeld & Stern, 1972). Other studies suggested that the length of the post should be equal to half of the root length (Jacoby, 1976); should be equal to 2 thirds of the root length (Larato, 1966); or at least halfway between the alveolar crest of the supporting bone to the apex of the root (Stern & Hirshfeld, 1973).

According to Standlee *et al.* (1978), the longer the dental post the more retention. Longer posts have more rigidity and less deflection compared with dental posts that have short length (Leary *et al.*, 1987). Stress distribution in the root can be influenced by post length, which, in turn, will affect the post's resistance to fracture. Moreover, increase in post length will increase its retention (Nergiz *et al.*, 2002). In a study by Cecchin *et al.* (2010), the authors concluded that teeth restored with long fiber posts (8 - 12 mm length) were more resistant to fracture compared with teeth restored with short posts (4 mm length). Similar results were published by (Sorensen & Martinoff, 1984), who reported that teeth restored with short posts had higher risk of tooth fracture.

On the other hand, some authors suggested that length of the post can negatively affect the teeth resistance to fracture; that is the longer the post the weaker the tooth. The authors related this to the more removal of the teeth structure in the apical part of the root (Guzy & Nicholls, 1979). However, some others (Giovani *et al.*, 2009) found that length of the cast metal post has no effect on the fracture resistance of teeth.

Another related factor is the amount of gutta-percha left at the apical area after post preparation. The most common concept in this regard is to leave at least 4 to 5 mm of root filling material at the apical part to maintain the apical seal (Camp & Todd, 1983; Mattison *et al.*, 1984). Some studies (Nixon *et al.*, 1991; Cleen, 1993; Rahimi *et al.*, 2008; Costa *et al.*, 2017) reported that teeth restored with posts and having less than 3 mm of gutta-percha showed more prevalence of periapical pathologies.

2.4.2 Post design

According to retention mode, dental posts can be classified into active or