Core build-up designs
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1.1 Introduction

Frequently dentists are confronted with teeth that are decayed in such a way that their vitality cannot be maintained, making an endodontic treatment indispensable. For such teeth adequate retention and resistance for crown and bridge restorations cannot be obtained without a core build-up restoration. These restorations replace coronal tooth structure that is lost as a result of excessive dental caries, previous restorations, or tooth fracture and can be fabricated with various techniques and restorative materials with or without the application of posts. The desirable features of core build-up restorations vary depending on clinical conditions. This thesis deals with \textit{in vitro} core build-up restorations for non-vital teeth and is intended to provide a scientific basis to the dentist for a proper selection of core build-up materials and techniques.
1.2 Core build-up restorations without a post

A core build-up restoration without a post is usually made from a direct restorative material and is indicated when the remaining coronal tooth structure is not sufficient to create retention and resistance for crown and bridge restorations. The physical properties of a core build-up material become more important as the residual tooth structure decreases [1]. Required properties may include adequate compressive strength to resist intra-oral forces [2], sufficient flexural modulus to prevent flexing of the core during intra-oral function [2], and good dimensional stability [3]; the latter requiring a coefficient of thermal expansion close to tooth structure [4] and minimal water sorption [5-7]. Other properties of importance are ease of manipulation, ability to bond to remaining tooth structure [8-10], biocompatibility [11], and a possible inhibiting effect on dental caries [12,13].

When retention and resistance form for a crown or bridgework are primarily dependent on the core material, the strength and retention of the core build-up can directly influence the durability of these restorations. For a tooth that must serve as an abutment to a fixed or removable prosthesis and is subjected to more unfavorable loadings, relatively more is demanded of the mechanical properties of the core build-up. For example, posterior teeth are exposed to higher functional loads than anterior teeth but the direction of these forces may be more perpendicular in the anterior region. Therefore, the required compressive and flexural strength may differ, depending on the location of the tooth in the dental arch. Another aspect is the esthetic property of the core build-up material, which should not adversely affect the esthetic qualities of the final restoration [14].

The four basic direct core materials are silver-amalgam, glass ionomer, resin-modified glass ionomer cements, and resin composite based core materials. Silver-amalgam has been reported to perform adequately as a core material under simulated clinical conditions because of its high compressive strength and rigidity [2,15]. Conversely, a number of studies have reported that glass ionomer cements performed poorly [16,17]. This may be caused by the fact that glass ionomer cements require several days [18] or even several weeks [19] to reach their maximum strength. Moreover the bond strength to tooth structure is relatively weak [20]. An advantage of these materials is their ability to release fluoride, which may inhibit dental caries [13]; although this effect is questioned by others [21]. Resin-modified glass ionomers perform better [22], but will probably not be suitable for large core build-up restorations or non-vital teeth [23]. Release of fluoride from these core materials can vary and for most of them this is largest during the first 24 hours, after which it gradually decreases [24].
Today the majority of core build-up restorations is probably made from resin composites. The main advantage of this material is that the core build-up can be made and shaped with high-speed intermediate burrs in one session. Initially resin composite restorative materials had a strength intermediate between silver amalgam and glass ionomer core materials [2], but later stronger versions became available [23,25,26]. Resin composites are more deformable than silver-amalgam, but this may be an advantage, because its elastic modulus is close to that of natural dentin [27]. Furthermore, adhesive bonding techniques provide mechanical retention for resin composite core build-up restorations to the remaining tooth structure [8,28,29] so that retention pins are not needed when substantial coronal tooth structure is present [30,31]. To some of them fluoride is added, but the amount of fluoride release from these resin composites is lower than for glass ionomer and the effectiveness is questionable [24]. For an adequate application of resin composite into the tooth preparation a syringe is recommended [32].

A disadvantage of resin composites is the shrinkage that accompanies the curing, which can cause stresses within the composite and the bonding interface. If the bond strength between core build-up composite and dentin is exceeded, partial debonding may take place, which might affect the success of the restoration. For this phenomenon the C-factor, which is the ratio of bonded surfaces to non-bonded free surfaces of the restoration, is accepted as an important factor for predicting the magnitude of the shrinkage stresses in bonded restorations [33,34]. An advantage for core build-up restorations is that the C-factor in most cases has a low value, because much free surface is available, which will keep the stresses relatively low.

Another concern is that many clinicians assume that chemical and dual-cured core build-up resin composites can be combined with the newer self-etching bonding systems. However, clinical experience has shown that some of these newer bonding systems fail to provide adequate bonding for chemical and dual-cured resin composites. Some recent studies ascribe the inferior bond strength to the acidity of the primer/bonding system [35-41].

The stability of the bonding layer is also a subject that receives continuous attention by investigators and recently it has been reported that deterioration of the hybrid layer and the decline of bond strength are the result of water sorption and/or fatigue loading [41-45]. Therefore conventional techniques based on mechanical retention may be preferred in cases where supporting dentin is limited [2].

Many factors can be decisive for the quality of core build-up restorations, but today consensus has been reached that the dentist should preserve as much coronal tooth structure as possible and try to avoid using endodontic posts [31,46-49]. Resin composite core build-up restorations without a post can also reinforce non-vital teeth. However, when mesial and distal surfaces of a posterior tooth are involved, partial coverage restorations should be preferred.
When complete crowns are indicated, cervical tooth structure should be preserved as much as possible to maximize the ferrule effect.

1.3 Core build-up restorations with a post

If a tooth is damaged so seriously that even more is demanded from the core build-up restoration, the retention of the core is frequently augmented by the placement of an intra-radicular post. In the Netherlands roughly 35% of endodontically treated teeth are “fortified” by posts. The ideal post should provide retention to the core and adequate seal of the root canal. It should support the core in such a manner that the cemented crown does not lose its attachment and that it strategically transfers forces to the tooth in order to prevent premature root fracture.

The concept of using the root canal of a tooth for retention of a core build-up and crown is not new. In the 18th century wooden posts were inserted into root canals of teeth to provide crown retention. Over time the wood could expand in the moist environment to enhance retention of the post until, unfortunately, the root often fractured vertically. Other efforts to develop crowns retained with posts or dowels in the 19th century were limited by the failure of the “endodontic” therapy. In the same century versions of metal posts, in which a porcelain-faced crown was secured by a screw passing into a gold-lined root canal, were introduced by Black. Further a device developed by Clark was extremely practical for its time because it included a tube that allowed drainage from the apical area of the canal.

1.3.1 Cast post and core restorations

Richmond introduced a crown in 1878, which incorporated a threaded tube in the canal with a screw-retained crown. This ‘Richmond crown’ was redesigned as a 1-piece post-crown to eliminate the threaded tube. The 1-piece post-crowns became unpopular because they were not practical when divergent paths of insertion of the post-space and remaining tooth structure existed, especially for fixed crown and bridgework. One-piece post-crown restorations also exhibited problems when the crown or bridge required removal and replacement. These difficulties led to development of a post-and-core restoration as a separate entity with a crown cemented on the core and the remaining tooth structure. With the introduction of endodontic therapy in the middle of the 20th century, the challenges for restorative dentistry increased. Teeth that were commonly extracted, without hesitation, could now successfully be treated with predictable endodontic therapy; however to save these severely damaged teeth for longer periods an adequate restorative solution was necessary. In this way cast posts and cores
became routine methods for restoration of endodontically treated teeth with moderate to severe destruction [60].

![Figure 1.1](image)

Fig 1.1 From left to right: custom-made cast post and core, prefabricated metallic, carbon and glass fiber posts with various shapes and surface designs.

Guidelines for the length of the post include a length equal to the length of the clinical crown of the final restoration [61], and two thirds to three quarters of the length of the root in the bone [62]. *In vivo* studies suggested that the clinical success of posts was directly related to their lengths. Therefore, it is rational to prepare a post channel as long as it is consistent with anatomic limitations and to maintain, minimally, 4 to 5 mm of apical root canal filling (*e.g.* gutta-percha) as a seal [63-66]. Another clinical study reported better results for parallel-sided serrated posts than for custom-cast tapered posts [67]. There is consensus that short posts are less retentive and put the root at risk because they can produce unfavorable leverage and shear stresses within the root canal, which may predispose the root to fracture [68,69]. Increasing the thickness of the post adds to its strength, but as this is at the expense of the supporting tooth structure, the effect may well be a reduction of the thickness and strength of the radicular dentin and the overall strength of the assembly [70].

Cast posts and cores have been reported to provide excellent service for endodontically treated teeth with moderate to severe damage. In 1989 a 6-year retrospective study of endodontically treated teeth with extensive loss of tooth structure, which were restored with cast posts and cores and crown restorations showed a 90.6% success rate [71]. A review study in 2002 reported an *in vivo* survival rate of 87.6% after 72 months for cast posts and cores in single rooted teeth [72], while a recent 10-year retrospective study reached 94% [73]. Cast posts and cores, fabricated directly or indirectly, are most appropriate for single-rooted teeth, especially for incisors and canines, and are still used as an integral component for crown and bridge restorations.
However, the fabrication of cast posts and cores has to be carried out in two visits and during the period of the temporary restoration contamination of the root canal may occur [74,75]. Therefore, single-session procedures should be preferred. Besides, with the recent advances in ceramic technology, the all-ceramic crown has become more popular. Restoring a non-vital tooth with a metal post and core in combination with an all-ceramic crown is complicated. The underlying metal from the post and core can alter the optical effects of a translucent all-ceramic crown and may compromise the esthetics. In response to the need for one-visit procedures and post and core restorations that possess optical properties compatible with all-ceramic crowns [14,76-78] other core build-up systems were developed.

1.3.2 Core build-up restorations with prefabricated metallic posts

For endodontically treated molars, core build-ups with direct restorative materials, which engage the pulpal chamber and a portion of the root canal, often perform adequately [79,80]. Retention of the core can be augmented by placement of one or more prefabricated intra-radicular posts.

Endodontically treated premolars are built up with either cast posts and cores or with prefabricated posts with cores of direct restorative materials. These prefabricated posts became popular, because the core build-up could be prepared in a single visit, did not require the removal of undercuts as for cast post and core restorations and saved the costs of the dental lab.

A variety of these prefabricated posts became commercially available and in 1994 a nationwide survey of dentists in the United States indicated that already 40% of the general dentists used prefabricated posts for the posterior as well for the anterior region [81]. The posts are supplied with various surface designs and shapes like parallel-sided or tapered shapes (Figure 1.1). Some parallel-sided posts are tiered and become tapered at the apical end where the root canal is generally narrower. Some prefabricated posts are passive, and others actively engage the tooth structure with threads [82]. Active posts are more retentive, but can generate unfavorable stresses and predispose the root to fracture [83,84]. The most retentive passive post is a long, parallel-sided post with a roughened surface, but this type of post often requires removal of substantial radicular dentin to achieve the desired length [65,69,85,86]. The clinical performance of these prefabricated post systems does not seem to differ much from the conventional cast post and core systems. For prefabricated posts in single rooted teeth a review study in 2002 showed that the in vivo survival rate reached 86.4% after 72 months [72]. In a recent 10-year retrospective study, in which radix-anchors were used, this prefabricated post reached a 80% success rate [73].
1.3.3 Core build-up restorations with prefabricated fiber posts

At the end of the 90's several non-metallic post systems became available. A post fabricated from carbon fiber reinforced epoxy-resin was developed in France by Duret and Renaud and became commercially available in Sweden in 1992 [87]. Carbon fiber reinforced epoxy resin is composed of unidirectional carbon fibers, which are 8 \( \mu \)m in diameter and embedded in a resin matrix. Later on glass and quartz-fiber based posts were also introduced to the market. Clinicians who support these types of posts claim physical properties more similar to natural dentin and sufficient resistance to high loads [27,88-94]. The posts can be fabricated from radiolucent or radiopaque material [95] and appear to be biocompatible [27]. Water sorption can weaken these posts and should be avoided [96]. Therefore, the post must be embedded in an impermeable cement layer, which may be achieved by using a resin composite luting agent for the cementation of these posts into the root canal [97-101], while the core build-up is fabricated of a resin composite restorative material.

Some \textit{in vitro} studies have shown that carbon fiber posts possess inferior strength compared to metal posts [102-105] and may be less retentive in the root canal [102]. However, one of these studies [105] also indicated that the carbon fiber post was quite stiff and strong, to a degree comparable to several metal posts and that the stiffness was related to the diameter of the posts. Remarkable was that the elastic limits of titanium posts were significantly lower than the elastic limit of carbon fiber posts of similar size; this may explain the observed fracture and failure of smaller titanium posts during clinical functioning due to masticatory fatigue loading.

Root fracture may be avoided by using fiber posts. \textit{In vitro} studies indicated that carbon fiber reinforced epoxy-resin posts were less likely to cause fracture of the root upon failure than metal posts [89,106-108]. This is contradicted by other studies that illustrated higher stress levels in the dentin for loaded carbon fiber posts systems than for cast post and cores [102,109,110].

A few retrospective, short-term, clinical studies that are available yet reported less than 3.2% failure after 2 to 6 years for carbon and glass-fiber reinforced epoxy resin posts [111-114]. However, other studies have shown higher failure rates for fiber posts and favor conventional metal post and core systems [115,116].

The fiber posts are manufactured in several configurations (Figure 1.1) and their ability to bond to adhesive resin composite appears appropriate and can be improved with mechanical retention such as serrations [117,118]. However, another study reported that serrations are unnecessary since the serrated parallel-sided stainless steel posts were not more retentive than either parallel-sided or tapered tooth-colored
posts; when all groups were considered, post dimension appeared to influence retention, with parallel-sided posts being more retentive than tapered posts [119].

Although the stiffness of these posts has been reported to be similar to human dentin, one study showed that the transverse modulus of elasticity for these posts exceeded the value of stainless steel posts [105,117]. Because of the parallel arrangement of the reinforcing carbon fibers, these posts display anisotropic behavior, whereby, their physical properties differ depending on the loading angles [117]. Besides, a larger diameter of the post will increase its rigidity [105] and smooth posts have been reported to be less flexible than serrated posts [105,118]. Furthermore, even if the elastic modulus of the posts is comparable to human dentin, this will not ensure similar clinical behavior for the post and the radicular dentin. The root is essentially a hollow tube and the thin rod-shaped post is within this hollow tube surrounded by an intervening layer of a luting agent with a lower elastic modulus. The different configuration between root and post combined with the intermediate luting material, suggests that the flexibility of the post will not match the flexibility of the root. A flexible post can be detrimental, especially when there is little remaining natural tooth structure between the margin of the core and the gingival extension of the crown. When a ferrule is absent or extremely small, occlusal loads may cause the post to flex with eventual micro flexing of the core; in this way the cement seal at the margin of the crown may be exposed to high stresses and may fracture in a short time. This can cause marginal leakage and result in caries, but the deterioration will be unnoticed until substantial destruction of tooth structure occurs [120,121].

1.3.4 Ceramic post and core restorations

With all the advances in ceramic technology also all-ceramic posts have been developed [77,78,122]. These posts are made from zirconium oxide or aluminum oxide, are radiopaque and have been reported to possess a flexural strength and fracture toughness similar to steel [88,105,123]. The high stiffness of these posts is subject to debate, because it may be likely to cause fracture of the root upon failure [89,93,124,125].

The posts were designed to support a resin composite core, but a large resin composite core may not be sufficiently rigid to support stiff all-ceramic crowns [2,6,126]. Therefore post and core systems entirely of ceramic material were developed. IPS Empress pressed-glass technology, with or without the use of a prefabricated zirconium post [77,127,128] can be used; another technique is by means of a Celay copy milling device that duplicates a wax model of a post and core from a pre-fabricated ceramic block [89]. Although ceramics are materials having high compressive strengths, they are brittle [105]. As an alternative to the all-ceramic post it is
possible to make an initial cast post and core from a metal ceramic alloy with a thin layer of opaque porcelain fused to the core portion, providing a durable post and core that will disguise the graying effect [129].

The ceramic posts were designed for adhesive resin cements, but some studies have reported poor bonding with resin cements between these posts and the intra-radicular dentin, before [100,130] as well as after dynamic loading or thermocycling [131]. Therefore additional conditioning of a ceramic post and core is recommended [132,133].

This new type of post system is not popular in clinical practice, as two visits are needed, less supporting tooth structure can be saved with indirect post and core systems, and the costs are relatively high. How well these posts resist intra-oral forces is unknown, as clinical retrospective studies on all-ceramic post systems are not available.

1.4 The ferrule effect and stress distribution

A post and core restoration can transfer occlusal forces intra-radically resulting in a predisposition of the root to vertical fracture [134,135]. The role of the final cast restoration in protecting the non-vital tooth has been discussed for decades. To prevent fracture of tooth structure, the importance of protective coronal coverage and a subgingival collar of cast metal to provide extra-coronal bracing were already mentioned in the 60’s [136,137]. The term “ferrule effect” was used for the first time in 1987 to describe the 360-degree ring of cast metal with the margin of the definitive cast restoration, situated at least 2 mm apically beyond the junction of the core and remaining tooth structure [138]. *In vitro* studies demonstrated an improved resistance to fracture when ferrules were used for post and core restorations [139,140]. Another study reported that, for full crowns, at least 1 mm of coronal tooth structure above the crown margin was needed to substantially increase the fracture resistance of endodontically treated teeth [141]. For endodontically treated premolars restored with full crowns, the fracture resistance was investigated for samples with and without cast posts and cores [142]; no significant difference was found between the two groups. These results indicated that the presence of a post did not influence the resistance to fracture, if the core was covered with a complete cast crown with a margin situated at least 2 mm apically beyond the junction of the core and remaining tooth structure. Another study on premolars indicated that failure of the cement seal of the crown started at the side of the tooth under tension, especially when the ferrule was small and the post was off-center [143]. Loss of the cement seal of the coronal restoration can be dangerous and before it is clinically detectable leakage can occur between the crown margin and the tooth surface and extend between post and intra-radicular dentin, which
can ultimately cause caries and loss of the tooth [120]. Recently the effect of the ferrule on the integrity of the cement seal of cast crowns was studied in vitro [144], and these appeared to improve the resistance to fatigue failure of the cement seal of a crown when the crown margin extended at least 1.5 mm apical to the margin of the core. The results of a retrospective clinical study [67] evaluating the survival and failure characteristics of teeth restored with posts and crowns showed a higher potential for fracture of the post when the crowns were placed in the absence of a ferrule. The contribution of post length and ferrule width in resisting dynamic loads was evaluated in another study [145]. This study showed that the ferrule width was more important in increasing fracture resistance to cyclic loading than post length.

On rare occasions when teeth are severely damaged, surgical crown lengthening [146] or orthodontic extrusion [147] have been performed to expose additional tooth structure to establish a ferrule. Further, molars can, in complex periodontal situations, be resected and restored with complex restorative techniques to avoid the need for large prosthetic restorations or removable prosthetic restorations, but these procedures are technically demanding and expensive and have relatively high failure rates, up to 38% in the first ten years [148]. If the provisions for developing a ferrule are impractical or the root to core build-up ratio is very unfavorable, extraction of the tooth should be considered. Replacement with conventional or implant-supported crown and bridge restorations can offer more durable solutions, with predictable techniques and clinical success rates over 90% [149,150].

The stress distribution of post and core systems with different designs was investigated. Two-dimensional photoelastic analysis was used to compare stresses generated upon loading of cast gold endodontic posts. The results demonstrated that in general the stress rose when the post diameter increased or large vertical loads were applied. Therefore posts with restricted diameter and preservation of tooth structure are recommended, particularly when bruxism is present [151,152]. It was reported that conservative enlargement of the root canal could make post placement unnecessary for largely intact teeth. If using a post, length has been found to be more important than post diameter for stresses in the cervical region; short wide posts induced high stress concentrations in this region. Post lengths beyond two thirds of the root depth did not further decrease cervical stresses but usually increased stresses in the apical region [153].

A later study used finite element analysis (FEA) to evaluate the distribution of stresses in dentin. Peak shear stresses occurred adjacent to the post at mid-root level and increased as the length of the post decreased. Peak tensile stresses occurred in the gingival third of the facial root surface, whereas peak compressive stresses were present in the gingival third of the lingual root surface. Conversely, the distribution of tensile and compressive stresses was not affected by a variation in the dimensions of the posts [69]. Other studies examined the influence of different
types of restorations placed following endodontic therapy, emphasizing the way in which forces applied to the occlusal surface were dispersed to the supporting structures of the teeth. The results indicated that the distribution and patterns of stresses vary depending on the direction of the loads and the type of restoration, and that these stresses are the highest in the apical and coronal region of the root canal [154,155]. Three-dimensional photoelastic models were used to study the effect of a ferrule on the stress distribution with cast post and cores. Strangely enough specimens with a 1.5 mm ferrule as a part of the post and core itself generated substantially higher mean stresses in the dentin than post and cores without a ferrule, but again the highest stresses were measured in the apical and the coronal region of the radicular dentin [156]. However, another study utilizing a prefabricated metal post with a glass ionomer core, reported that crown restorations with a ferrule of 1 mm demonstrated a significantly higher resistance to fracture; crowns without a ferrule showed twice as many vertical root fractures [157].

Concerning the design of the post, a multi-tiered metal post system may distribute stress more symmetrically than the single-tiered, metal post systems or even carbon fiber post systems [102,158]. A study of the influence that the type of core material has on the stress distribution indicated that a stiffer core material can shift the load from the apex to the coronal region [159-161].

1.5 Luting cements

The successful use of posts in root canals is partly dependent upon the properties of the luting cement. Important properties of luting cements are their compressive and tensile strength and their adhesive characteristics for forming a bond to both the post and radicular dentin. Of importance also are the amount of shrinkage during setting, the extent to which they absorb water, and last but not least, their handling characteristics [162]. Today's most commonly used luting agents are zinc-phosphate, glass ionomer, resin-modified glass ionomer, and resin composite cements. Each of these cements have their advantages and inherent disadvantages [163]. Zinc-phosphate cement has been used for decades and this cement has been extremely successful. The primary disadvantages of zinc-phosphate cements are solubility in oral fluids and lack of adhesive properties. The advantages are the good handling characteristics, dimensional stability and low shrinkage during setting. Unpublished data of shrinkage measurements in our department showed values as low as 0.3%.

Glass ionomer cements provide a weak chemical bond to dentin [20] and may have a potential benefit by releasing fluoride [13]. However, the ability of glass ionomer luting cements to inhibit caries in dentin is disputed [21]. A disadvantage of glass ionomer cements is their slow
setting, which requires several days [18], or even several weeks [19] to reach maximum strength. This makes these cements less suitable for cast posts and cores since vibrations generated during recountoring of a cast post and core with a bur, soon after cementation, may weaken the immature cement film, and lead to retentive failure of the post.

Resin-modified glass ionomer cements also release fluoride [164,165]. However, release of fluoride from these core materials is variable and for most of them this is largest during the first 24 hours, after which it gradually decreases [24]. A point of concern is that resin-modified glass ionomer cements imbibe water and as a consequence expand with time [166-168]. Dependent upon the thickness of the cement layer, volumetric expansion may cause vertical root fracture. Nevertheless, this type of cement is often used in clinical practice for cementing post and cores and therefore investigations should be done to evaluate this phenomenon.

Resin composite cements basically are insoluble and in vitro provide better retention for intra-radicular posts than glass ionomer and zinc phosphate cements [169-172]. Other studies have reported inconsistent results, but these may be explained by the large variety of conditions encountered in the root canal [173-179].

One factor that may be responsible for the varying results is the geometry of the root canal, where the ratio of the bonded and the free non-bonded surface areas of the resin-composite cement layer (C-factor) is very unfavorable [101]. This can result in high contraction stresses during setting that even might exceed the bond strength to either the post or intra-radicular dentin. The possibility of flow to relieve these stresses will be even more restricted for the abruptly setting light-curing resin cements than for the slower setting chemical-cured cements [180].

Another aspect is the conversion of dual-cured resin based luting agents. Inferior bond strengths to root dentin were reported for a dual-cured resin composite cement that was allowed to cure only chemically, while additional photo-initiation showed better results [181], although the light intensity may be insufficient in the apical area of the root canal.

Dual and chemical-cured resin composite cements are provided with self-etching primer systems for bonding to dentin and the acidity of these systems may interfere with adequate bonding [35-40]. When a neutral bonding agent was applied as an intermediate layer between cement and dentin better results were reported [182].

With regard to leakage, better results have been reported for adhesive resin composite cements than for non-adhesive cements when used for crown restorations [183]. Also in root canals, in spite of the very unfavorable C-factor, less leakage has been reported for resin composite cements than for non-adhesive cements like glass ionomers and zinc-phosphate cements [184]. It is obvious that this aspect is of importance for the prognosis of the endodontic
treatment [185-187]. The timing of the preparation for the post after endodontic treatment may also affect the final result; less leakage was found when endodontic treatment and post cementation were carried out in one visit [188].

If endodontic sealers contain eugenol and the obturation of the root canal occurs by condensation of gutta-percha under pressure to force the sealer into the dentinal tubules and lateral canals, eugenol will penetrate the dentin. This is difficult to remove and it may affect the setting of the resin cement, as free-radical addition polymerizations can be inhibited by phenolic compounds, such as eugenol (2-methoxy-4-allyphenol) [173]. However, one luting agent can be more susceptible to this effect than another. Also endodontic sealers without eugenol may disturb adequate adhesion of the luting agent when sealer and gutta-percha remnants stay behind after the preparation for the endodontic post [178,179,189].

A negative effect on the bond strengths of resin based cements to root canal dentin has also been reported after irrigation with sodium hypochlorite solution (NaOCl), which is generally used in endodontic treatments [190,191], although contrary results were found by others [192]. This negative effect may be prevented by an extensive washing with a 10% ascorbic acid solution [191].

The ability of resin composite cements to bond to dentin and restorative materials can enhance retention, but this increased retention may not always ensure resistance to dislodgment of the post under clinical conditions. One study that reported extremely high retentive values for an unfilled resin composite cement [172] showed that this relatively weak cement allowed plastic deformation that will possibly lead to fatigue failure in vivo [193,194].

Adhesive resin cements are also technique sensitive [49,174] and can be difficult to manipulate. In particular resin composite cements often show an accelerated setting under oxygen free conditions like those encountered in the apical part of the root canal. Primers that contain initiators can even intensify this accelerating effect on the setting of cement and can seriously shorten the working time. When a Lentulo paste carrier is used to distribute the resin composite cement into the root canal, premature setting of the cement may occur and as a consequence the post cannot be placed completely into the prepared part of the root [49]. To avoid these problems the cement can be applied only on the post before it is seated into the root canal. However, on the other hand this method involves the risks of air entrapment deep down in the prepared canal and as the post is seated the air will travel through the liquid cement to create voids that will compromise the physical properties and the retention of the posts [173]. Filling the canal with cement before seating the post can avoid air entrapment and provide a more dense and uniform cement lute. Zinc-phosphate cements seem especially well suited for placement in the canal before seating of the post, because of their extended working time [195] Even better
results are obtained when the cement is injected into the root canal by means of thin syringes [196].

Until now there are no long-term clinical studies of cemented posts that demonstrate the superiority of a specific cement. Depending on the type of post system, an appropriate luting agent must be selected (e.g. adhesive or non-adhesive) and, most important, recommended procedures should be strictly followed [73].

1.6 Failure of post and core restorations and the anatomy of premolars

Endodontically treated premolars are often provided with restorations involving endodontic posts to ensure success. Unfortunately, failures of these restorations still occur, which leads to disappointment and extra costs. The causes of failure for any tooth have been investigated in a number of clinical studies [60,63,67,71,197]. These studies suggest that failures are due mainly to the mechanical properties of the post and core. High failure incidences are especially expected to occur with relatively short posts or deficient ferrules [121,145] with deterioration of the luting cement around the post caused by fatiguing from functional loading [120]. However, the anatomy of premolars may frequently be incompatible with the application of long endodontic posts. There may be exterior radicular grooves, running from the cemento-enamel junction to the apical area [198], a converged shape of the root canal(s), a buccal root which is vulnerable to perforation [199], and variants in the root canal system anatomy (1,2,3 rooted and different levels of furcation entrances) [200]. In addition, premolars with post and core restorations are more vulnerable to root fracture than other teeth due to the narrow mesial-distal dimension of the root; especially the second upper premolar is notorious [201-203]. For these reasons the preparation procedures should be as non-invasive as possible and the use of endodontic posts should be avoided if adequate retention for an adhesive resin composite core build-up can be obtained from the residual dentin [51,107,135,204]. Moreover, for its sealing quality the apical root canal filling has to be preserved as much as possible [187,205]. When partially removed for an endodontic post, a remaining apical fill of 5-6 mm should be preferred [66,206,207], which frequently results in a limited post length. However, short posts that are rigid, create unfavorable stress distributions in the root at the apical level [69] and can put the root at risk. Therefore, short posts with a flexibility more close to that of the tooth structure may be preferred for premolars, as stresses on the core may be better dissipated along the post in the direction of the apical part of the root.
1.7 Investigation methods in literature

Despite the large volume of published research on core build-up restorations there is no consensus how to restore a heavily decayed teeth. There are numerous *in vitro* studies describing different restorative approaches, primarily for non-vital teeth, but data from these investigations are frequently conflicting [49]. Also several retrospective clinical studies of restored non-vital teeth and literature review studies have been performed [63,72,73,208,209], but also the results from these studies do not allow us to formulate clear clinical guidelines for post and core restorations. Another reason for confusion is the fact that in the last two decades many new core and post materials have become available to the market.

With all retrospective studies there are problems with controlling the treatment methods. Patients who are surveyed in a retrospective study often receive a treatment procedure selected by clinical judgment of each individual case. Teeth with minimal remaining coronal dentin may have been restored with cast posts and cores, and those with substantial residual tooth structure may have received prefabricated posts or foundation restorations without posts. Consequently, with this treatment protocol, the teeth restored with cast posts would be at a higher risk of failure, not because of any inherent problems with the procedure, but because the dentists selected cast posts and cores for teeth with the least supporting dentin and with the poorest prognosis.

Randomized controlled clinical trials would provide the most reliable data, but these studies are very expensive and long-term data would be unavailable for many years. Moreover these investigations are subject to the cooperation of the patient and individual factors, such as functional and parafunctional forces, and oral hygiene [48,49].

*In vitro* studies are in the majority, where it is easier to standardize the conditions. Many investigations have examined the retention of different kinds of post and cores, related to the features of post and core or luting agents [210-214] and the fracture resistance of post and core restoration [94,131,215-218]. Some of these studies evaluated the fracture resistance of crowns cemented over cores to mimic more clinical conditions and the influence of the crown ferrule [104,121,145,219]. When fracture resistance was used to evaluate these restorations, the loading angle substantially altered the results [220].

To mimic chewing conditions other studies added fatigue loading onto the post and core (and crown), before testing the fracture resistance [2,106,121,145,215,221-223]. Also leakage patterns of different post and core restorations were investigated, with and without fatigue loading [121,184,187,224-226].

It can be concluded that many factors can be decisive for the durability of core restorations on endodontically treated teeth, with or without posts. The ideal post provides durable retention
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to the core and an adequate seal of the root canal. It supports the core in such a manner that, if a crown is cemented upon it, it does not lose its attachment and strategically transfers forces to the tooth in order to prevent premature root fracture.

To develop one single test setup that answers all questions related to failure is impossible. Nevertheless, clinical experience in daily practice with failures of post and core restorations on premolars brought the author of this thesis back to the university to investigate aspects that may be decisive for durability.

1.8 Aim and outline of this study

As shown in the previous survey many studies on fracture resistance of post and core restorations were carried out in the past. However, variation in the size and shape of post, core and crown may be responsible for the wide variance of the data in these investigations. Because premolars in particular proved, clinically, to be susceptible to failures [60,63,67,71,203] these teeth were chosen as specimens for this investigation as they represent, more or less, the worst case scenario under clinical conditions. Due to the anatomy of premolars relatively short posts (6 mm) were used in these studies.

The first aim of this thesis was to investigate the fracture resistance of different core build-up designs (with and without an endodontic post) with special attention to standardization of the test specimens. To mimic the clinical conditions as much as possible full crowns were cemented over the post and core. To exclude variations in the size and shape of post, core and crown a test setup was developed in which the coronal sectioning of the endodontically treated premolar, the preparation of the core, and the crown were standardized; this study is described in Chapter 2.

Premolars were collected from children that needed extraction of premolars for orthodontic reasons. Information forms and sets of small self-sealing plastic bags and instruction forms (see Appendix) were sent to a number of orthodontists. When extraction of the premolars was indicated the children were asked to contribute to this investigation by leaving their extracted premolars with the dentist that extracted them. If they agreed, they received the set of small plastic bags and an instruction form, which they had to give to the dentist on the following visit. In this form the dentists were asked to wrap a wet piece of tissue around the extracted teeth and put them in the plastic bag, which had to be securely closed with the self-sealing strip, and to send them in an envelope to our department. In this way the premolars were protected from dehydration. Many premolars were collected; the children that donated their premolars received a present in return.
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When this study was started there were not many published in vitro investigations, in which fracture strength was evaluated before and after fatigue loading. Clinical studies suggested that chewing forces could play a prominent role in failures because the post, which had to provide adequate retention for the core, came loose. Therefore, the second aim of this thesis was to evaluate the influence of fatigue loading on the quality of the cement layer between the post and the root canal wall. A test set-up was developed, in which the placement of a crown with a ferrule was deliberately omitted to exclude any external strengthening effect on the post and core. This configuration was believed to be the most severe with regard to the resistance to failure and was considered appropriate for specifically evaluating the fatigue behavior of the cement layer between post and intra-radicular dentin.

In Chapter 3 this cement layer was studied for conventional cast post and cores, of which half of the samples were cemented with an adhesive resin composite cement and the other half with the non-adhesive zinc-phosphate cement. In Chapter 4 the same test set-up was used to evaluate the cast post and core, and three types of prefabricated posts with an adhesive resin composite core; for all specimens the same adhesive resin composite cement was used as the luting agent. In Chapter 5 the third part of this investigation involved specimens that were restored with a carbon fiber post and an adhesive resin composite core. Three types of adhesive luting agents were used to cement the carbon fiber posts and were evaluated before and after fatigue loading.

Assuming that endodontically treated teeth do not need to be reinforced by means of a post, because the dentinal hardness and moisture content of non-vital teeth are similar to vital teeth [50,227] and that enough retention can be obtained from the residual tooth structure for a resin composite core build-up restoration, the bond strength of the resin composite core build-up to the tooth structure is of paramount importance. However, dentists are not always using bonding systems according to the manufacturer’s instructions. Total etch bonding systems, two-step bonding systems and one-step bonding systems are often exchanged to bond chemical-cured build-up composites. Recent studies have shown that the bond strengths can be severely affected if incompatible combinations of bonding systems and resin composites are used. [35-37,39,40]. Therefore the third aim of this thesis, described in Chapter 6, was to evaluate the shrinkage stresses of chemical and light-cured core build-up composites during setting, their bond strength to dentin, and their compatibility to different types of bonding systems.
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