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Biomimetics and the restoration of the endodontically treated tooth

Biomimética e a restauração do dente tratado endodonticamente

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ABSTRACT

Although much progress has been obtained in terms of the Endodontic treatment, the literature shows that true success can be only achieved with adequate coronal seal to avoid bacterial contamination, and protect the tooth structure from fracture. There are many options available to the clinician to restore the endodontically treated tooth; however, there is not much evidence available on what alternative is better than another. This review will critically present the current knowledge on restorative choices, including posts and endocrowns, showing advantages and disadvantages of different treatment forms. With this knowledge, we will also introduce the concept of biomimetics to endodontically treated teeth, and how the nature of their remaining tooth structure can benefit from this approach. This concept entails the use of mechanisms and biologically produced materials to restore a tooth in a way that would mimic its natural structure, with the purpose of achieving better long-term prognosis.

KEYWORDS

Endodontics; Dental restoration; Biomimetics; Adhesion; Tooth fracture.

RESUMO

Embora tenha se obtido progresso em relação ao tratamento endodôntico, a literatura mostra que o sucesso real só pode ser atingido com o selamento coronal adequado, para evitar-se a contaminação bacteriana e proteger-se a estrutura dental de fraturas. Há muitas opções disponíveis para o clínico para a restauração do dente tratado endodonticamente; entretanto, não há muita evidência disponível sobre qual alternativa é melhor que a outra. Esta revisão apresentará criticamente o conhecimento atual sobre opções restauradoras, incluindo retentores intraradiculares e *endocrowns*, mostrando vantagens e desvantagens das diferentes formas de tratamento. Com esse conhecimento, também introduziremos o conceito de biomimética, uma vez que dentes tratados endodonticamente, devido a natureza de sua estrutura dental remanescente, podem se beneficiar desta abordagem. Esse conceito envolve o uso de mecanismos e materiais produzidos biologicamente para restaurar um dente de forma a imitar a estrutura natural, com o objetivo de alcançar melhor prognóstico de longo-prazo.

PALAVRAS-CHAVE

Endodontia; Restauração dental; Biomimética; Adesão; Fratura dental.

INTRODUCTION

The ultimate goal of endodontic therapy is to prevent or eliminate the development of apical periodontitis [1], which includes the adequate conclusion of the treatment with a proper restoration that will prevent recontamination. During root canal treatment, there are multiple components that each play a role in the overall success of the procedure. This includes the elimination and/or reduction of bacteria from the canal system, followed by a tight seal between the oral cavity and periradicular tissues to prevent recontamination [2].

Following disinfection of the root canal system, a prompt restoration is required to avoid microleakage that could cause an endodontic failure or fracture of the remaining tooth structure, with deleterious effects of coronal leakage on the success of root canals. Bacterial products were found at the apex of root-filled teeth after 3 months in the absence of coronal restoration [3], and showed the deterioration of apical healing in cases with poorly sealed coronal restorations [4].

With current available evidence supporting the need for an adequate restoration, efforts should be directed towards rebuilding devitalized teeth using techniques and materials that mimic the physical and mechanical properties of the natural tooth. This concept is known as biomimetics, which refers to the use of a variety of mechanisms and biologically produced materials to restore a tooth in a way that would mimic its natural structure [5]. Endodontic treatment entails access to the root canal system which oftentimes involves removal of caries and additional tooth structure to gain access. This compromises the structural integrity exhibited by the natural tooth. The final goal is to build a restorative framework that has similar physical properties to a natural tooth [6].

This review will present the current knowledge on the use of restorative options, while also introducing advanced biomimetic concepts to improve the prognosis of endodontically treated teeth.

CURRENT KNOWLEDGE ON EVIDENCE-BASED OUTCOMES AND CLINICAL RECOMMENDATIONS

The restoration of endodontically treated teeth has largely been studied from both restorative and endodontic perspectives and yet has rendered few conclusive results. Several classical studies provide specific evidence-based clinical recommendations that acknowledge the loss of structural integrity and differences in dentin following endodontically treated cases [6-9]. Access preparations, caries, and existing restorations compromise the structural integrity of the tooth and thus often contribute to tooth fracture [7]. Additionally, although there is evidence stating that the dentin still maintains the same resistance [8], common sense establishes that endodontically treated teeth are less resistant [9]. The differences in endodontically treated teeth make the restorative process complex and controversial. It is commonly established, however, that prognosis of a tooth with pulpal and periapical disease is dependent on both proper endodontic therapy and a proper definitive restoration after endodontic treatment [10].

In this context, there were attempts in the literature to observe the success of root canal treatment and its association with an adequate restoration. Studies on the restoration of endodontically treated teeth have rendered that, especially when bared to substantial loading forces, restorations that enhance structural integrity and resistance are expected to improve prognosis [10-12]. An assessment on if the type of restoration associated to the tooth group has relevance in the outcome are available, but there are suggestions that anterior teeth with minimal loss of tooth structure and integrity may be restored with a bonded restoration to fill its access opening [11]. Posts and crowns should not be considered unless there is minimum remaining natural tooth structure [10]. Heydecke's study compared the fracture strength and survival rate of sixty-four caries free maxillary incisors with approximal class III cavities and different core build-ups [12]. The study found that the final restoration of endodontically treated anterior teeth can be successfully performed by restoring the endodontic access with composite while also observing that the cementation of endodontic posts offers no advantageous fracture resistance. A retrospective study that include *in vitro* studies confirm that filling the access of anterior teeth is an appropriate treatment option [11].

In general, it is agreed that endodontically treated posterior teeth should receive full cuspal coverage. Pantvisai and Messer studied cuspal deflection in molars in relation to endodontic and restorative procedures and concluded that cuspal deflection increased with increasing cavity size and was greatest following endodontic access [13]. These findings support the importance of cuspal coverage to reduce the risk of marginal leakage and cuspal fracture in endodontically treated teeth [14]. Aquilino and Caplan completed a retrospective study that looked at the association between cuspal coverage and the survival rate of endodontically treated molars. The study found that endodontically treated teeth that did not receive full cuspal coverage following endodontic treatment were lost at a six times greater rate than teeth crowned after obturation [15]. Most retrospective studies have shown that, in general, crowns are more efficient in terms of increasing the success rates [15,16]. Other authors even analyzed the time span between the end of the root canal treatment and the placement of restoration and found that success rates decrease with time, where the authors showed that teeth not crowned within 4 months after obturation were extracted at a 3.0 to 6.0 times greater rate than teeth crowned right after obturation [15,17]. This points out a strong association between crown placement and the survival of endodontically treated teeth which may impact treatment planning if long-term tooth retention is the primary goal [15]. However, it is important to emphasize that direct restorations can be performed, especially on anterior teeth or teeth with a good number of well-preserved walls. In general, crown placement has no significant effect on the success of anterior teeth but significantly improves clinical success rates of posterior teeth [11]. These data support the concept that crowns generally should be used on endodontically treated posterior teeth and on anterior teeth with substantial loss of tooth structure [18,19].

The literature available for restoring endodontically treated teeth comes with major limitations. For *in vitro* studies, evidence is highly limited in its application to clinical recommendations due to a lack of specificity and account for uncontrolled variables. *In vitro* data disregard essential clinical elements to patient specific outcomes that include but are not limited to caries risk, parafunctional habits, and occlusion determinants [20]. Additionally, *in vivo* data are questionable as the impact of the elasticity of tooth structure, the periodontal ligament, and alveolar bone in success and prognosis are not considered [11]. Although the evidence is convincing for retrospective studies, the problem with the studies cited is that they investigate large databases but with no specifics to the details involved in the restorative process. Few details are provided on the type of restoration and isolated outcomes for each one of them. Clinical data rarely provide information about the initial tooth biomechanical status nor do they provide details of protocol and technique during the restorative process, and therefore fail to provide significant outcomes if the type of restoration associated to the tooth group has relevance in the outcome [20].

There is a wide diversity of published opinions in relation to restoring endodontically treated teeth and ultimately may lead to less-than-optimal treatment selections. With the limitations provided above, we do not have good quality of evidence to support one or another type of restorative procedure for endodontically treated teeth, besides common-sense and careful interpretation of the results available. The evidence for restoring endodontically treated teeth should be improved by a more specific case selection protocol that includes information about specific details about pretreatment and treatment statuses and technique.

POSTS AND ENDOCROWNS

There are a number of factors impacting clinical performance of endodontically treated teeth restored with posts and crowns. In general, the literature suggests that posts should be used only when the coronal portion cannot be retained by another means [21]. This data can be corroborated by other studies reporting success in restoring endodontically treated teeth with crowns without posts when there are a number of remaining coronal walls and adequate dentin height [22-24]. Nevertheless, when posts are deemed necessary, it is better to perform a post preparation with no delay from the obturation [25]. In this context, when considering teeth with remaining coronal walls, both cast and prefabricated posts may be used. In the absence of a ferrule, posts with high values of elastic modulus are indicated [26], as *in vitro* observations have found that cast post and core systems lead to more irreparable failures compared to fiber post systems regardless of the amount of remaining root tissue [27].

Even though the literature has no good evidence on the survival rates for cast versus prefabricated posts [28], there is some evidence showing that premolars benefit more from prefabricated adhesive posts as custom posts increase the odds of critical failure for this group of teeth [24]. Additionally, a randomized clinical trial showed that self-adhesive luted prefabricated posts achieved high long-term survival rates irrespective of using a glass fiber or a titanium post [29]. For anterior teeth, in the absence of ferrule, the use of fiberglass posts represents a conservative choice due to homogeneous stress distribution, compared to the stress concentration into the root canal presented by cast post. The length of 7 mm for cast post and cores seem to produce high rates of root fractures [30].

Another important aspect to be considered when restoring the endodontically treated tooth is the presence of a ferrule (Figure 1). The called "ferrule effect" can be defined as a circumferential dentin collar of 2 mm or more in height [29,30,31]. Overall, a ferrule represents a determining factor in the strain, fracture resistance, and fracture pattern [30] that will increase tooth strength due to the remaining coronal dentin, and untimely, improve the long-term prognosis [24, 32]. Evidence from *in vitro* and *in vivo* studies shows that the presence of ferrule has a positive effect on the fracture resistance of endodontically treated teeth [24,33]. Thus, in order to provide a ferrule, strategies such as crown lengthening or orthodontic extrusion should be considered, or even obtaining an incomplete ferrule is better than a complete lack of ferrule [34]. Interestingly, another study found that when adequate ferrule is provided, type of post, final restoration, and luting agents, have less impact on the performance of endodontically treated teeth [34]. Finite element analyses have shown greater values of stress, including the cervical region, associated with the absence of ferrule suggesting that ferrule could enhance stress distribution [35].

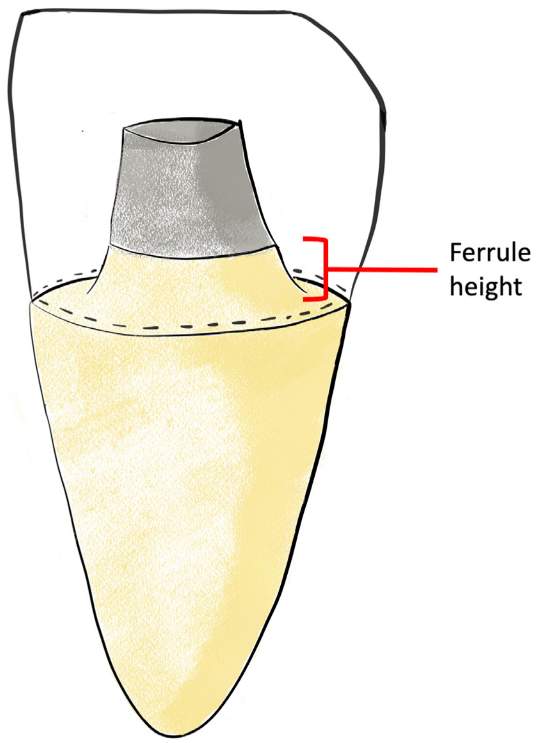

Figure 1 - Schematics showing the dentin collar, responsible for the ferrule effect. The higher the height and longer the circumference [30,31,33], the best the prognosis will be on the survival of posts.

Following the advent of CAD/CAM and adhesive methods, intracoronal restorations called "endocrowns" emerged as a possibility to reconstruct damaged posterior teeth [36]. Their advantages include good resistance and quick restoration, little preparation compared with posts and cores, no interference in the root with retention based on macromechanical fixation in the pulp chamber [37], similar or better longevity compared to traditional post/core systems [38,39], potential to increase fracture resistance of restorations [40,41], and stabilization of weakened tooth structures [42]. The literature has shown that teeth restored by endocrowns are potentially more resistant to failure than those with fiber posts. Under physiological loads, ceramic endocrowns cemented in molars are more resistant to damage or debonding [41]. Disadvantages of endo crowns include difficult removal, possibility to expose root canals to external environment, and need for at least 2 mm of pulp chamber depth to be effective, although they may present a conservative approach depending on the clinical conditions [43].

ROLE OF BIOMIMETICS IN IMPROVING THE ENDODONTIC PROGNOSIS

Endodontically treated teeth often present a restorative challenge as these teeth are structurally compromised with deep caries, cracks, several missing walls, and extensive previous restorations. The marked reduction in cuspal stiffness and strength of the teeth is attributed more to the missing coronal structure than to additional dentin removal during conventional endodontic treatment. It was proven that endodontic procedures reduced the relative cuspal stiffness of premolar teeth by only

5%, in contrast to an occlusal cavity preparation (20%) and a mesio-occluso-distal (MOD) cavity preparation (63%). For these reasons, preservation of tooth structure is important for its protection against fracture under occlusal loads and for its survival [7]. As stated above, there is no consensus regarding the choice of the final restoration for endodontically treated teeth. Most restorative decisions are driven by factors such as missing proximal walls, remaining dentin, and nature of the root canal structure. Historically, devitalized teeth were restored with cast post and core which involved extensive preparations and removal of dentin. Advances in adhesive dentistry have allowed more tooth conservation.

Teeth are naturally multiphasic, with enamel that acts as a compression dome, transforming and transferring loads to the dentino-enamel complex (DEC) into primarily compressive loads in the dentin [44]. The DEC is a stress bearing interface that prevents the underlying dentin from damaging tensile forces that it is not designed to handle. The primary load bearers of the tooth are the peripheral rim of enamel, the sub-occlusal transverse ridges and the biorim: the area of the tooth that lies below the maximum point of convexity. These structures act as a rebar that buttress the tooth from top to bottom and side to side, resisting fracture. Any restorative procedure, be it direct or indirect, that invades these natural load bearing structures lead to significant loss in the fracture resistance of the tooth. To effectively mimic the physical and mechanical properties of the tooth, efforts should be directed towards minimally invasive techniques that preserve these load bearing structures while using materials and techniques that would reconstruct the multiphasic layer of the tooth.

In 2002, Deliperi and Bardwell introduced what became known as "Stress reduced direct composite" [45]. This protocol involves restoration of enamel and dentin as two different substrates using selective composite placement in 1mm increments, and light curing techniques to minimize polymerization stress, thus allowing for a better stress distribution throughout the entire tooth [14,46]. It is known that human enamel comprises of 95% hydroxyapatite. It is hard but brittle, yet it survives the deleterious effects of occlusal loads without cracking. Its compressive strength is 384 mPA, so it is built to withstand compression, but it is weak under tension with a tensile strength of 10-40 mPA. As we get closer to the DEJ, the inorganic content is reduced to 85%, with 25% organic matter compromising primarily of collagen [47]. Collagen reinforces the underside of the enamel much like rebar reinforces a concrete beam. With a tensile strength of 44-105 mPA, dentin is a more resilient and tougher than enamel. Its higher organic content makes it more compliant to withstand higher tensile stresses than enamel [48]. With this understanding of the natural structure of a tooth, one could attempt to truly restore a tooth using materials that mimic this composition and stress bearing capabilities. In the case of enamel replacement, ceramics such as feldspathics or lithium disilicates are most appropriate. Their tensile strengths are 25-40 mPA which is close to the tensile strength of enamel. For dentin replacement, there are a subset of composite materials which approach a tensile strength of 40-60mPA which is similar to dentin [49]. Identifying and utilizing these materials is a core concept of the biomimetic approach to restorations. In 2017, Deliperi et al. introduced the use of ultra-high molecular weight woven polyethylene fibers as part of the "Wallpapering technique" for restoration of devitalized teeth [50]. The strategic adaptation of polyethylene fiber to the residual cavity walls was aimed towards a shock absorbing and crack shielding mechanism similar to the DEC. It required no additional tooth preparation and therefore was considered a more conservative approach to restoring endodontically treated teeth (Figure 2). Another approach would be the use of dental fragments which, although not extensively studied, has shown good results in a clinical case report [51].

Often with structurally compromised teeth that are endodontically treated, there comes a point in the restorative continuum that the bonded direct restoration reaches their limitation. This includes scenarios where the functional and nonfunctional cusps are compromised. The biomechanical integrity of these teeth can be restored with indirect restoration, specifically onlay and non-retentive overlays that are minimally invasive and present as a biomimetic and a more fracture resistant alternative to traditional crown preparation [52]. It eliminates the need for complex geometrical design such as steep walls and sudden transitions that would otherwise concentrate stress and lead to reduced fracture resistance and unfavorable outcomes. In addition, onlay and overlays mitigate stress

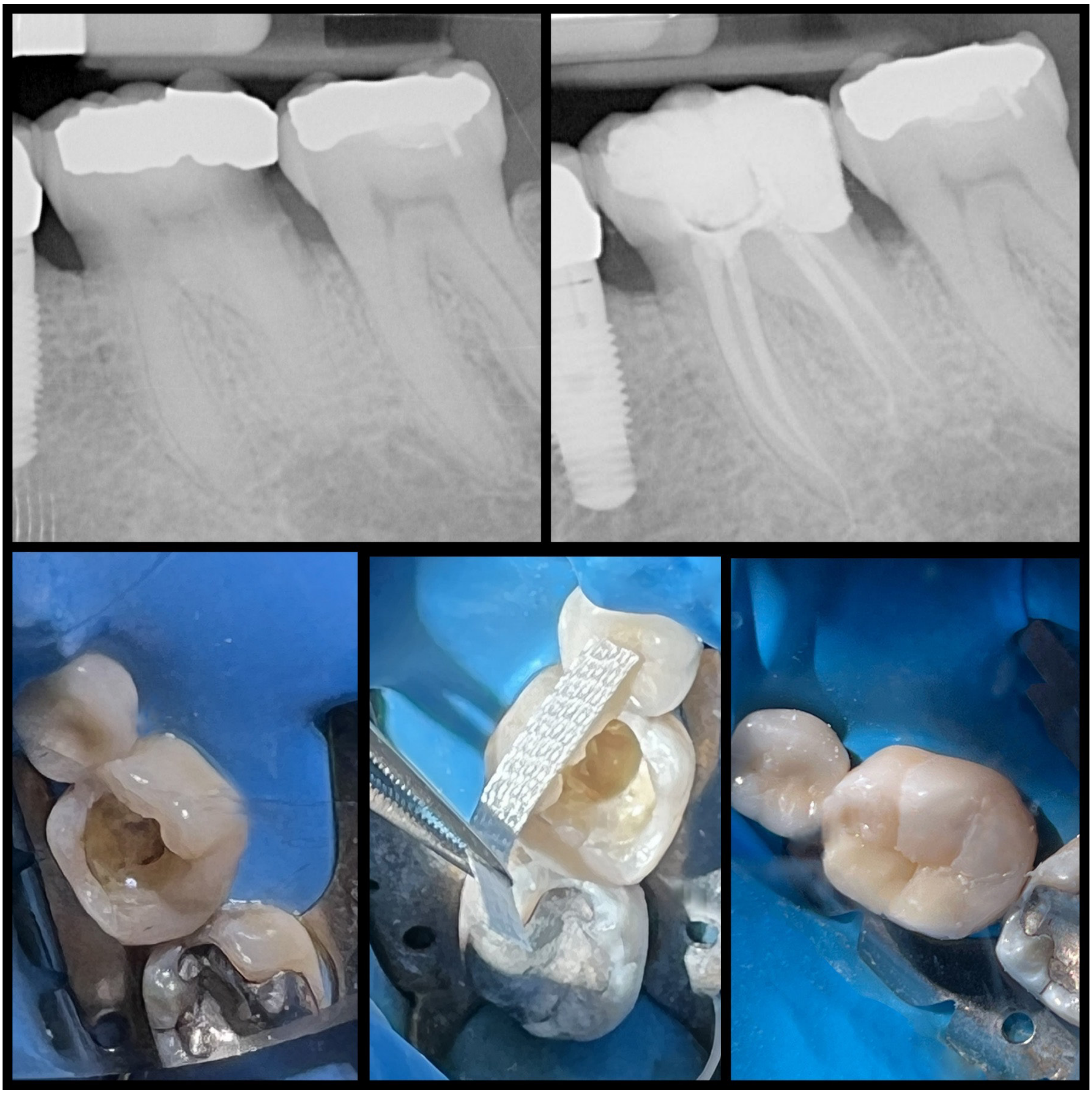

Figure 2 - Example of a clinical case of "wallpapering technique" in an endodontically treated tooth. The patient had financial concerns and could not afford a crown coverage. To improve the probability of success, a polyethylene fiber was adapted within all walls of the cavity and the tooth was restored with composite. Courtesy of Dr. Kimble.

by providing a highly compressible ceramic framework over the height of contour which mimics the natural enamel compression dome, while preserving the healthy tooth structure below the height of contour, or biorim (Figure 3) [53].

Both the direct and the indirect approach rely heavily on the strength of the underlying adhesives. This is crucial for retention of direct restoration, sealing against microleakage and to increase the fracture resistance of indirect restorations. Several bond-maximizing techniques can be incorporated starting with establishing complete caries and crack removal during endodontic treatment. Adjunct methods include air abrasion of the tooth structure for better bond strengths, beveling enamel across the enamel rods, and employing gold standard bonding systems, specifically third or sixth generation bonding system that can achieve a bond strength of 35 mPA to enamel and 60 mPA on dentin [54,55]. In addition, immediate dentin sealing and resin coating for better bond strengths. For this, bonding agents are applied at the time of tooth preparations or

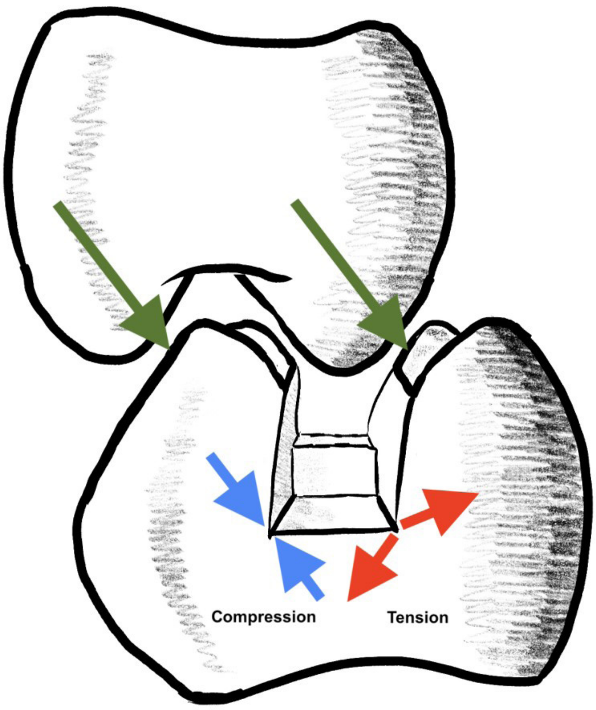

Figure 3 - Schematics of the tension/compression effects on the tooth cusps. The cusp suffering tension is more likely to develop a crack or fracture when compared to the cusp suffering compression. This can guide the treatment decision to cover, at least the cusp under tension.

before capturing an impression for an indirect restoration. This is followed by resin coating, where a 0.5 mm layer of flowable resin is applied on to the developing adhesive/hybrid layer. This ensures that the adhesive is fully polymerized, limiting gap formation and ensuring a secure bond [5]. Immediate dentin sealing and resin coating addresses the fundamental problem in adhesive dentistry where the polymerization shrinkage stress exceeds the early dentin bond strengths leading to delamination of the adhesive and the composite, setting the stage for microleakage [56]. To address this concern, the newly bonded dentin surface must have time to "mature" before being loaded by the shrinkage stresses of the incoming composite resin restorative material. Maturation entails a wait time of 5-30 mins. When allowed to mature, dentin bonding can reach a bond strength of 55-60 mPA, this equates or even exceed the strength of the DEJ. In addition, immediate dentin sealing increases the bond strength of indirect restoration by 400% [57].

Leveraging these advanced adhesive concepts for direct and indirect restoration that replicate the stress bearing capabilities of a natural tooth are crucial to improving the survivability of endodontically treated teeth.

FINAL CONSIDERATIONS

It is clear that the adequate restoration of an endodontically treated tooth remains a challenge, particularly because there is a lack of evidence from high quality clinical trials showing that one treatment is superior to another. Most of the information available comes from retrospective clinical studies and/or from *in vitro* data, which although necessary to point to some variables of importance, lack the prospective aspect and the level of confidence to direct clinical decisions. Even current systematic reviews conclude that fact [58,59], and this can be a call for more well-designed clinical studies to help clinicians in their treatment planning.

Even with these limitations, it is clear that endodontically treated teeth can benefit from a biomimetics approach. This fact is even more evident when it is well known that cracks can reduce the long-term prognosis and this approach can help to contain or, at least, to mitigate the effect of the crack's distribution on the tooth structure. Our understanding of stress distribution on teeth that have gone through significant endodontic procedures are due to benefit from our understanding of appropriate restorative techniques.

Author's Contributions

PK, MS, BC: Conceptualization. AMC, MSC,PK, MB: Methodology, Validation, Formal Analysis, Investigation, Writing – Original Draft Preparation. PK, BC: Visualization. MB, BC: Writing – Review & Editing.

Conflict of Interest

The authors have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

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Regulatory Statement

As a literature review, this manuscript does not qualify as a study on human subjects, thus being exempt of regulatory statement.

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