Optimizing the restoration of posterior endodontically treated teeth

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CHAPTER 1

Introduction
An undeniable trait of living beings is their attempt to adapt to new situations and unfavorable conditions in order to survive. Some of these attempts take place within a lifespan, like phototropism of plants following a light source, while others come in the shape of mutations over multiple generations like industrial melanism of arthropods adapting to urban pollution. Humans have shown multiple adaptation changes over the time like the persistence of lactase after childhood that appeared with the increased breeding of cows and consumption of milk, or the shape of teeth that accommodated different diets. In addition to the unintentional adaptation in the form of genetic mutations, humans benefit from the consciousness attribute. That ability allows to identify a problem, investigate the causes and to actively find a solution or a way to avoid it in the future. This quality is also useful in cases lacking of flaws but that could still profit from an amelioration or optimization, like gaining time in a process, reducing required energy to perform a certain task or enhancing the overall performance. This concept can be applied in most branches of our lives, and is widely studied in mathematics and then applied in engineering and design. As an example, different ways exist to construct a building that would fit a hundred people safely and the quest of optimization would be to study the best possible combination of required material quantity and type, structure design, building technique and other different factors. This can also be applied to finance, marketing and to practically every other domain. All these questions are mostly solved through rigorous calculations and simulations, with the inclusion of well-studied safety factors. One thing that is not done in civil engineering is to adopt a building design based on the retrospective number of fallen structures, simply because the repercussion on lives would be catastrophic and because it is an empirical manner of reasoning. This is unfortunately the case in part of medical and dental research where recommendations are made based on accumulated failure rates of treatments made by different operators, on different patients, under uncountable varying factors. It is possible to observe that so far, the best designer of dental structures remains nature with its most complex and efficient components generated by
millions of years of optimization. This can be seen clearly in the combination of dentin’s capacity to absorb energy and enamel as its wear resistant protective layer. This optimized design extends to the roots of the tooth embedded in the periodontal ligament that acts like a shock absorber and the pulpal tissues with irreplaceable reparative and sensory functions. For the previous reasons, it is given that ideally more effort should be invested in the preservation of the capital of natural dental tissues in any way possible, by avoiding mutilation of hard tissues and devitalization of teeth. If prevention cannot be enhanced and does not unfold efficient in maintaining this organ in a functional physiological state for a continuously extending lifetime, only then would conservative treatment approaches become important to keep what is left of that well-designed blueprint which is currently hard to replicate.

The word currently is of essence because despite that time advantage of nature over human products, in some rare applications, artificial is outperforming nature, such as computer memory or the capacity of a machine to outperform the best players of chess or Go in the world. Surrendering to the actual reality, and still far from the situation where endodontic treatments become obsolete, more than fifteen million root canal treatments are performed annually in the United States according to the American Dental Association, and it is important to identify the elements that precede it and conservative measures have to be taken to arrest the already extended damage and avoid the ultimate no return step of extraction.

**Detrimental agents of dental tissues**

Alteration of dental tissues can be divided into physiological and pathological changes, with the latter having a relatively faster pace. Teeth are in the center of essential daily activities like nutrition and speech which makes them naturally prone to deterioration under multiple external factors, which exhibits in fractures or the underestimated erosion and micro-cracks. Attrition, that is caused by contact between two dental surfaces, is one of those physiological factors that could transform into a pathological state in cases of bruxism. The same applies for
abrasion, which is the effect of external elements getting in contact with dental tissues, like the unavoidable physiological contact with food, or the pathological aggressive brushing or irregular habits of chewing objects like dermatophagia for example. For the chemical reactions that also participate in changing dental tissues, it can be divided into lesions with or without bacteria involvement. The first type which is erosion or also called corrosion is the effect of acid present in food which is usually countered quickly by the presence of saliva. Acidic dissolution of dental tissues involving bacteria, is the most common cause of tooth deterioration and is the main symptom of caries, which depends on multiple factors and is aggravated by poor oral hygiene and frequent consumption of fermentable carbohydrates. Reduced salivary secretion, which manifests in dry mouth or xerostomia, accompanies radiotherapy or the ingestion of some medications and has severe implications on acid-related lesions since saliva is an essential medium for buffering and remineralization.

Tooth devitalization

If not treated properly, aforementioned loss of enamel and dentin would eventually lead to infection and or exposition of the pulp. Preserving dental tissues is a mutual responsibility of the patient and the dentist, and should be based on prevention and on a conservative approach of treatment. From the patient side, awareness about dental health is becoming more accessible through more information on nutrition and oral hygiene. A leap forward was observed in the dental field with the emergence of adhesive dentistry which made minimally invasive intervention possible. Despite these advances, patients’ negligence and wish to function optimally with their teeth resulting in prosthodontic needs are still often accelerating the loss of tooth vitality. The final mediation before devitalization could be in the form of pulp capping, but if the pulp exposition is large, the symptomatology or the infection are irreversible, an endodontic treatment should be performed. The goal of this work is to present some of the differences between vital
and pulpless teeth, identify areas with still some space for adjustment, and to propose some optimization possibilities in regards to improving the quality of the treatment or even simplifying the restoration of endodontically treated posterior teeth.

**Changes of a devitalized tooth**

It can be seen that in the recent years that implantology is one of the most investigated and promoted subjects in dentistry. However, preventing the multiple reasons that lead to teeth loss should be given the same or even more attention than restoring oral function. It was reported that around half of the extractions of endodontically treated teeth was due to a catastrophic fracture\(^2\).\(^4\). It was also estimated that up to 7.5% of endodontically treated teeth (ETT) require extraction within the 5 years following the treatment\(^5\).\(^7\). Even though it is widely believed that pulpless teeth are weaker than vital ones, it is important to understand that necrosis or absence of the pulp is not the major criterion for that supposed fragility. The mechanical consequences of vitality loss can be therefore divided into the few direct effects resulting from the necrosis or absence of the pulp and the more extensive indirect impact of the endodontic treatment procedure along with the preceding hard tissue damage by caries or trauma. From the direct effects of vitality loss, it is believed that a minor dehydration of 9% is detected in the tissues\(^8\),\(^9\). Many studies have shown that loss of water does not appear to have a significant effect on reduction of mechanical properties of dentin\(^10\)-\(^12\). On the other hand, a more relevant direct effect could be the loss of proprioception\(^13\) and increased pain threshold\(^14\) that would lead to increased loads on pulpless teeth. Lowenstein and Rathkamp\(^13\) showed that pulpless teeth require a stimulus that is around 57% higher than vital teeth in order for the patient to sense it. Concerning the indirect factors that are presumed to be responsible of the significant reduction of fracture resistance of treated pulpless teeth, extensive hard tissue removal at the coronal and radicular levels seems to be the most important one\(^15\).
Endodontic access cavity

In order to access the root canals, in most cases intact dental hard tissues still need to be removed affecting directly the fracture resistance of the tooth\textsuperscript{16-20}. In traditional endodontic cavity (TEC), the type of cavities that was used since the early stages of endodontics and that is still currently dominant (Fig. 1.1), it was calculated that up to 23\% of the volume of coronal dentin and enamel is removed in the process\textsuperscript{19}, and that it reduces tooth stiffness by 5\%\textsuperscript{21}.

\textbf{Figure 1.1:} Schematic representation of a) traditional endodontic cavity, b), c) two different configurations of conservative endodontic cavities.

Despite the relatively low stiffness reduction, such tissue removal increases cuspal deflection which could then generate more fatigue microcracks and subsequent fractures\textsuperscript{7,22-24}. As seen in the Figure 1.1, TEC aims to remove the totality of the pulp chamber roof in order to reduce interference between endodontic instruments and the cavity walls, and to allow a direct access for the files. Studies have shown that reducing the amount of dentin removal, especially in posterior teeth, is beneficial in terms of increasing fracture resistance\textsuperscript{19,21,25-28}. Conservative endodontic cavities (CEC) were developed as less invasive alternatives\textsuperscript{27,29,30}. This approach consisted of drilling very small cavities on the occlusal surface, without the obligation of removing the totality of the chamber roof (Fig. 1.1). A cone beam computed tomography (CBCT) is often necessary in order to plan the most convenient access location to attain the different canals. Some studies showed that CEC presented fracture resistance values comparable to intact teeth\textsuperscript{16,19,26}, while
other studies showed that CEC did not significantly improve that resistance\textsuperscript{31}. Conservative access cavities come with the risk of possibly neglecting infected tissues in the pulp chamber or even inappropriate root canal treatment due to the handicapping small access\textsuperscript{19,27,29-32}. A study by Krishan R. \textit{et al}. showed that in teeth with CEC, up to 63\% of the surface of the canals was left untouched by the endodontic files\textsuperscript{27}. The clinical consequences of such results were not investigated but it could possibly lead to lower healing rates since mechanical preparation of the canals and especially the apical part was proven to be crucial to remove the necrotic tissues and biofilm\textsuperscript{33-36}.

\textit{Canal preparation, irrigants and obturation}

Since mechanical preparation of root canals is essential to effectively remove or reduce the biofilm from the canal walls and bacteria present within the depth of dentin tubules, which cannot be solely done with irrigants\textsuperscript{37-40}, this removal of tooth hard tissues is unavoidable. Mechanical preparation of root canals, by means of manual or rotational files, has shown to add more fragility to ETT, which can be seen by comparing fracture resistance of prepared and unprepared canals\textsuperscript{41-45}. It is also known that the more dentin is removed from the canals, the greater the effect on reducing fracture resistance of the tooth. This means that files with higher tapers, like for example the majority of rotational files that may reach a taper of 11\%, are prone to weaken the tooth more than conventional manual 2\% taper files. Some studies have also shown that rotary instruments might be capable of inducing cracks in the root\textsuperscript{46-51} with a prevalence of up to 35\% of the treated cases\textsuperscript{52,53}. Self-adjusting files (SAF) are new hollow endodontic instruments made of nickel-titanium alloys with an abrasive surface and an inner channel for continuous irrigation that goes until the tip of the instrument. Due to their design and deformability, they are able to take the shape of the canals attempting to get in contact and to prepare all the surface of the canal walls\textsuperscript{54-56}. Some studies have shown that canals prepared with SAF presented higher resistance to fracture than rotary file systems\textsuperscript{57,58}, while
contradicting results were also found in a study of Capar I. et al.\textsuperscript{59}. In traditional endodontic procedure, cleaning is completed by the use of syringe with needle to deliver irrigants. Since liquid coming out of the needle cannot go more than 1.5 mm beyond the tip\textsuperscript{60-64}, the needle has to be inserted as close as possible to the working length to be able to have an effect in the apical zone. The smallest needle tip diameter that is commonly used in endodontics has an outer diameter of around 0.3 mm, which entails the need for additional apical dentin removal if this irrigation technique needs to be used\textsuperscript{65-67}. Since the section cut of the canal in that region is not often round, manual and rotary instruments can be considered more invasive than SAF that avoids excessive removal of dentin sound tissues by adapting to the oval form of the canal and delivering irrigant to the working length without the need for a wide apical preparation or risk of irrigant extrusion\textsuperscript{68}. It was also shown that SAF are less likely to induce cracks in the roots\textsuperscript{49,50,69}. Methods and technologies have been developed to clean root canal systems without any usage of mechanical instrumentation. Lussi A. et al. first described a non-instrumental technique in 1993 based on controlled hydrodynamic cavitation\textsuperscript{70}. Through a custom-made system, sodium hypochlorite was introduced inside the root canals at alternating pressure fields to allow penetration and renewal of the liquid within the canals. Primary results were promising\textsuperscript{70-72}, but a clinical study also including Lussi as a co-author in 2002 revealed that this technique is still not efficient for clinical use, since an increased quantity of organic debris was still left in the canals\textsuperscript{73}. However, non-instrumental techniques are still developing, and new systems like photon-induced photoacoustic streaming and multi-acoustic are becoming more frequently used. Another concept in endodontic therapy not depending on traditional instrumentation, is the usage of glutaraldehyde for the fixation of remaining pulp tissues and bacteria instead of targeting its removal. In 1983, Wemes J.C. et al. described this technique and showed high success rates of 96% over a 5-year clinical investigation\textsuperscript{74}. This technique was nonetheless not developed further due to biocompatibility concerns of glutaraldehyde. The previously described non-
instrumental and limited instrumentation root canal treatment techniques could potentially implicate better fracture resistance of the teeth since dental hard tissues are preserved. Irrigants used in root canals can also play a detrimental role on the tooth tissues\textsuperscript{75-77}. Dentin is made up of 22% of organic matter by weight\textsuperscript{78}. Sodium Hypochlorite (NaOCl) is a proteolytic agent and therefore affects the collagen in dentin, and was shown to increase the strain and reduce its modulus of elasticity\textsuperscript{77,79-83}. Ethylenediaminetetraacetic Acid (EDTA), another common chelating product used in endodontic treatment was shown to have multiple effects on dentin’s mechanical properties, like reducing fracture resistance and microhardness\textsuperscript{75,84-87}. Obturation techniques and materials also have a direct effect on the mechanical properties of the tooth\textsuperscript{88}. Lateral condensation technique is prone to induce cracks and exert more forces on the root than other techniques like warm vertical compaction or carrier-based thermoplasticized technique\textsuperscript{45,89-91}. As for the materials, bonded endodontic obturation fillers appear to have a reinforcing effect on the tooth\textsuperscript{87,92-94}.

\textit{Defect cavity configuration}

Aside from the weakening resulting from loss of vitality and endodontic treatment, coronal defect size and configuration are the most affecting elements to the fragility of ETT. This subject was studied since more than sixty years through a destructive testing method, and Vale W.A. was able to show, using control and test contralateral premolars, that when the bucco-lingual width of the class II equals one-third of intercuspal distance, the fracture resistance was two-thirds of the intact tooth\textsuperscript{95}. In general, removal of dental hard tissues increases the deformation of the remaining tissues under load\textsuperscript{21,96-101}. Strain and linear displacement measurements are two main non-destructive in-vitro methods to study that deformation. Reeh E.S. \textit{et al.} studied the relative stiffness of multiple cavity types using strain gauges\textsuperscript{21}. In their findings on premolars, occlusal cavities reduce stiffness of intact teeth by 20%, while a two-surface defect reduced it by 46% and mesio-occluso-distal (MOD) by 63%. For Linn J. \textit{et al.}, MOD cavities on endodontically treated molars reduced
stiffness by 40%. Other similar studies measured the cusp deflection or linear displacement of different cavity types using linear variable differential transformers. Cusps of intact teeth showed the lowest deflection of up to 1 µm, while extensive MOD cavities showed a deflection of up to 5 µm per cusp. After opening the access cavity and eliminating the pulpal roof, cusp deflection increased to 16.5 µm. High values of up to 50 µm were found in isolated cusps. A comparison of deflection between 7.5 µm for MO and 16.5 µm for MOD cavities also shows the important role that marginal ridges play in the coronal structure and that reduction in stiffness is not only volume dependent, but also dictated by the configuration of the missing tissues. These two testing methods allow measurements to be done on the same tooth right after each cavity type, which eliminates the factor of variability between different teeth. All the previous results indicate that removal of hard tissues preceding and during endodontic treatment increases the deformation of enamel and dentin. This increase has multiple consequences on the tooth and the adhesive/restorative material that could appear on the short or on the long-term. Concerning the dental hard tissues, higher deflection under daily cyclic loads accentuates fatigue and microcracks formation. This also reduces the strength of the tooth, and therefore more fractures can occur on ETT. The impact on the adhesive interface can also be very detrimental by causing micro-gaps that would favor micro-leakage and possibly worsening the prognosis of the tooth due to secondary caries or even debonding.

Restoration of moderately damaged teeth

Before addressing the restorative part, it is worthy to note the difference between survival rate and mode fracture. A lot of publications focus on presenting a number of years of service of different types of restorations while stressing less on the importance of the mode of failure. Between a treatment that presents a survival time of 10 years with a 90% chance of catastrophic failure and another treatment with 5 years survival time and 50% catastrophic failure, the latter would probably be
the better option. It is the responsibility of the dentist to clearly present the multiple possible treatments to the patient along with the different risks, in order to choose the most suitable one. Restorative treatment following the endodontic procedure is a key step that could either reduce the deleterious effects of the previously mentioned degradation or exacerbate them. Multiple investigations studied the deformation of restored and unrestored dental cavities\textsuperscript{95,96,98,99,102}. Before adhesive dentistry, a first way to decrease excessive cuspal deformation on ETT was proposed by reducing and covering the remaining cusps to redirect the occlusal forces vertically rather than laterally\textsuperscript{103,104}. Metallic cusp-covering restorations had either butt-joint margins or reverse marginal bevels that better transferred occlusal loads to the remaining dental structures after endodontic access cavity and MO or MOD cavities, while amalgam fillings without cusp coverage did not strengthen the remaining structures\textsuperscript{96}. Therefore, besides being more invasive, non-adhesive intracoronal restorations like amalgam have zero effect on increasing the tooth resistance to fracture\textsuperscript{95}. A second way of reducing cusp deflection emerged with adhesive restorations that held together the remaining structures\textsuperscript{98,105-107}. Several clinical studies exist on the performance of adhesive restorations without cusp coverage like Manhart J. \textit{et al.} who reported high success rates of 100% at 3 years for ceramic inlays and 89% for composite inlays on premolars and molars\textsuperscript{105}, and Mannocci F. \textit{et al.} with similar success rates of 90% for direct composite restorations on premolars reinforced by a fiber post\textsuperscript{108}. Despite positive results on the short-term for restoration of MOD without cusp coverage, onlays and full coverage restorations are still the recommended treatment option for posterior ETT since they present higher success rates on the long term\textsuperscript{109}. These advantages in terms of clinical performance still come with some drawbacks as the process still often necessitates removal of sound dental tissues. As seen in previous sections and though multiple studies, removal of dental hard tissues has a negative impact on tooth strength. Moreover, such large restorations are often made using indirect techniques and therefore require the work of a lab-technician or a CAD/CAM system. Such additional
steps increase the costs for the patient and also the duration of the treatment, especially if no chairside system is available. For those reasons, and since MOD cavities are very common and can be considered an unfavorable cavity type in terms of mechanical resistance on ETT, this subject was addressed in Chapters 2 and 3 of this research and a novel non-invasive reinforcement technique of such teeth was proposed through first a proof of principle finite element analysis (FEA) and then an in-vitro fracture strength and mode study.

Restoration of severely damaged teeth

In cases more severely damaged than MOD cavities presenting reduced or no coronal tissues, a new issue arises besides tooth fragility, which is the mean to retain the coronal restoration. Traditionally, and since adhesion did not exist, crowns could either be placed around the remaining coronal tissues if sufficient ferrule is present, or anchors in the form of pins, screws or posts were often considered necessary to build a core and retain the future restoration\textsuperscript{110,111}. Severely damaged ETT restored with posts show higher survival rates than counterparts without a post\textsuperscript{112-116}. This is only valid for cemented crowns, while the opposite was observed in studies comparing bonded crowns with and without posts\textsuperscript{117-120}. Posts can be made through different direct and indirect techniques, and are available in multiple materials like fiber-reinforced, metal and ceramic. Important mechanical characteristics of dental posts are flexural modulus which reflects the bending deformation and flexural strength which is the maximum bending stress before rupture. Metallic posts can be either prefabricated or cast, with a flexural modulus of up to 200 GPa\textsuperscript{121} they were the golden standard for years, and were thought to be beneficial to the tooth’s mechanical resistance. Being stiff materials, failure is almost always catastrophic due to the redirection of forces deep within the root, therefore causing unrepairable fractures\textsuperscript{122-124}. Cast metallic posts appear to perform better than prefabricated metallic posts in terms of less catastrophic failures and higher survival rates\textsuperscript{125}. Fiber-reinforced posts then emerged, and they were also either prefabricated or
customized by adapting bundles of flexible unpolymerized fibers to the canal morphology. Prefabricated fiber posts appear to have higher survival rates than customized ones\textsuperscript{113,126}. The fibers of such posts can either be glass, carbon, quartz and polyimide. Their flexural modulus is around 45 GPa\textsuperscript{121} which is closer to dentin’s (around 17 GPa)\textsuperscript{127,128}. This seemingly narrower difference of flexural properties showed in some studies that catastrophic fractures with fiber posts became less frequent and repairable\textsuperscript{126,129-134} since the forces were more homogeneously distributed across the material and especially at the adhesive interface\textsuperscript{123,135-138}. Contradictive results showed similar or even higher root fracture rates for teeth restored with fiber-reinforced posts\textsuperscript{123,125,139}. Concerning survival rates, no conclusive results exist on whether fiber or metallic posts perform better. Individual clinical and in-vitro studies vary a lot, with some showing that fiber posts have lower survival rates than metallic posts\textsuperscript{140}, and other studies showing no difference or better survival rates\textsuperscript{114,125,132,139,141,142}. A significant factor that appears to be agreed upon by most studies is the effect of the volume or quantity of remaining coronal tissues irrespective of the type of posts that is used, which is recommended to be at least one axial wall or higher than 50% in volume\textsuperscript{113,143}. A ferrule of a minimum 1.5 mm to 2 mm high remaining coronal tissues, appears to have an important impact on the survival rate of severely damaged ETT\textsuperscript{117,144-149} and it appears that teeth with reduced or no ferrule have higher survival rates when restored with fiber posts rather than metallic posts\textsuperscript{114,150}. Possibility of fracture of fiber-reinforced post-and-core was also shown to be higher than the fracture of the metallic\textsuperscript{151}. Failures of fiber-reinforced posts are mostly debonding\textsuperscript{114,126,131,132,140,152-156}, particularly because intracanal adhesion is challenging due to a highly unfavorable C-factor and the type of radicular dentin\textsuperscript{144,157-159}. Some studies also showed micro-gap formation between the dentin and luting agent\textsuperscript{160-162}. Another hindering factor is the curing of the post luting agent since light penetration is limited with increased depth.
Endocrowns

With the evolution of dental adhesion techniques and systems, other restorative approaches differing from post-and-core became possible to restore severely damaged ETT. Endocrowns are single-material mono-block crowns that have an extension inside the pulp chamber. This gives endocrowns significantly higher thickness of material which increases the fracture strength compared to traditional crowns. Another clear advantage of endocrowns is conservation of intracanal tissues that are often removed before post placement in post-and-core restorations. This also implies better stress distribution instead of concentrating it in the weakened roots like restorations with posts generally do. Aside from sparing excess intraradicular tissue removal, endocrowns preserve coronal tissues by not requiring specific margin preparations like most regular crowns do, and are also advantageous in cases of limited interocclusal space. This not only allows to save sound dentin that enhances fracture resistance of the tooth, but it also maintains cervical enamel that is essential for long-term integrity of the marginal adaptation and quality of the adhesion at this level. The clinical procedure is simpler than traditional post-and-core techniques and the costs are also lower. Clinical studies have showed good survival rates of more than 90% for endocrowns, with failures presented as fracture of the ceramic restoration and recurring caries. Concerning fracture strength, some in-vitro studies showed higher values for endocrowns compared to crowns with radicular posts, while other studies showed similar values between the two. Despite the low number of existing clinical studies, a recent systematic review of Sedrez-Porto J.A. et al. showed very favorable survival rates of endocrowns between 94% and 100% up to 3 years. The length of the endocrown extension in the pulp chamber can go up to the pulp chamber floor in multi-rooted posterior teeth, or can be set by the clinician in single rooted premolars. In order to understand the effect of that length on the marginal adaptation of endocrown restorations and on the resistance to fracture, an in-vitro...
study comparing endocrowns with extensions of 0 mm, 2 mm, 4mm with traditional post-and-core crowns is presented in Chapter 4.

**Materials for endocrowns**

After detailing multiple changes that occur to the tooth tissues and structure, the complement restorative material should also be addressed. As already clearly established, so far, no artificial material can replace natural missing dental tissues in a perfect way. It is true though that multiple materials exist and perform very well, but they can be qualified as alternatives and still not a substitute. Restoration of a dental defect can be divided into multiple aspects: Filling the space, allowing mastication, reestablishing esthetics, ensuring biomechanical integrity. Some flaws still exist in accomplishing these functions in an exact matter as natural dental tissues do. For example, most dental restorative materials perform well in terms of recreating the missing portions of the tooth, but there are some limitations in recreating the original “perfect” mix of biomechanical properties, adhesion to the tooth and esthetics. For the restoration of ETT, a range of materials for both direct and indirect applications can be used, like metals, ceramics and composites. The two latter have proven good results in terms of esthetics, biomechanical properties and marginal adaptation\(^{131}\). A main difference between post-and-core crowns and endocrowns is that the latter is monolithic while the former is usually made of multiple materials and presents multiple interfaces. Some studies have shown that having one restorative material is better from the mechanical point of view\(^{178,179}\). In the case of endocrowns, multiple studies have shown that the choice of material has a significant effect on the biomechanical performance\(^{177,180}\). Stiff materials like lithium silicate and zirconium oxide are often associated with higher stress concentration in dental tissues whereas more flexible materials like resin composites tend to transfer the forces in a more natural pattern\(^{180,181}\). Resin composite blocks used for endocrowns appear to have higher fracture strength\(^{177,182,183}\) and more favorable fracture mode represented by less catastrophic failures as seen in a study
of El-Damanhoury et al.\textsuperscript{182} who showed no catastrophic failure for resin composite endocrowns against 70\% of catastrophic failures for lithium disilicate endocrowns. This higher flexibility is however accompanied by higher microleakage than feldspatic and lithium silicate ceramics. Another important factor that affects the fracture strength of a restoration and its long-term survival is the quality of adhesion and the type of luting agent, which plays a key role in stress distribution. In that context, it was shown that resin nano ceramic blocks adhere better than ceramics to resin luting agents\textsuperscript{184,185}.

Effect of luting

Multiple types of luting agents exist, with variations in chemical composition, filler and matrix type. For ceramic and resin composite restorations, resin-based luting agents are the most recommended since they allow adhesion through the methacrylate function present in the monomer\textsuperscript{186}. Resin-based luting agents can also be classified according to the polymerization mode and viscosity. Before discussing these two aspects, luting agents englobe the materials that are conceived and dedicated for the cementation of dental restorations, which will be referred to as luting cements, and the materials that are intended for restoring missing dental tissues but can also be used for the cementation of dental restorations, like restorative resin composites. The polymerization of resin-based luting agents can be started by either photoinitiators (light-curing), or by a mixing of two chemicals (self-curing), or by the combination of both mechanisms (dual-curing). Polymerization mode has a direct effect on the setting time of the material, which itself affects multiple aspects like ease of excess removal, seating and color stability\textsuperscript{187-189}. Light-curable luting agents have a clear advantage since the setting is directly tied to the presence of an adequate light-curing source, and the clinician is in control of that process allowing the time to make sure that the restoration is seated properly and eliminate most excess material before hardening. Simultaneous cementation of multiple restorations is therefore easier and more predictable since working time is
not limited. This also avoids removal of bulk polymerized material with burs at the margins which could stress the interface and compromise its integrity. Polymerization mode also affects the degree of conversion of the luting agent, especially in situations with limited curing light penetration. Propagation of light undergoes multiple variations when it passes from one medium to another. Light waves coming out of a light-curing unit (LCU), and passing from air into a translucent dental restoration material, are not completely transmitted through that material. With increased thickness of the material, and with the decrease of translucency, the irradiance and energy emitted by the LCU is significantly attenuated by the restoration that acts like a filter. Irradiance varies between 400-500 mW/cm² for low irradiance LCUs, and 1400-1700 mW/cm² for high irradiance LCUs, and delivered energy is the product of irradiance by the time of light-curing. Dental resin based materials require around 16 J/cm² to achieve sufficient polymerization. In cases with reduced or no light penetration, it is possible that this required energy does not reach the luting agent or that it requires an excessive irradiation time. The current literature recommends using dual-curing cements in thick restorations without clearly defining the characteristics of a thick restoration. Frequently, however, usage of dual-curing cements is being done in a systematic manner, without evaluating case-by-case the possibility of using light-curing luting agents, which present the previously mentioned advantages. Another important notion that should not be overlooked is that dual-curing cements still require adequate light curing in order to reach acceptable clinical performance. Relying on the self-curing component of such materials is not enough to obtain the necessary conversion rate. Regardless of the polymerization mode of dental resins, insufficient polymerization has multiple severe implications on the clinical survival or the restoration. From the biomechanical point view, this translates into reduced physical properties, reduced adhesion and an increase of monomer leaching. From an esthetic perspective, wear and staining of the resin is increased. Therefore, ideally, a classification of restoration configurations based on light-curing possibility and optimal light-curing
strategy, including time and light source position, should be elaborated instead of only considering the thickness of the restoration as an absolute limitation to photopolymerization. Chapters 5A and 5B discuss these matters, and show the efficiency of using light-curing luting agents under a thick but “light-curing capable” restoration by favoring more translucent pathways than throughout the restoration. Viscosity and filler volume are other elements where restorative resin composites have the upper hand over regular luting cements. Most of the latter are less filled and have lower viscosity and modulus of elasticity than restorative resin composites. This means that restorative resin composites have better physical properties, which is essential to the durability of the restoration. Additionally, low viscosity materials tend to flow beyond the margins of the preparation, into the gingival pocket, which complicates its removal especially in the interproximal area.
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