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## Review

# Resin composite—State of the art

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### ABSTRACT

**Objectives:** The objective is to review the current state of the art of dental composite materials. **Methods:** An outline of the most important aspects of dental composites was created, and a subsequent literature search for articles related to their formulation, properties and clinical considerations was conducted using PubMed followed by hand searching citations from relevant articles. **Results:** The current state of the art of dental composites includes a wide variety of materials with a broad range of mechanical properties, handling characteristics, and esthetic possibilities. This highly competitive market continues to evolve, with the major emphasis in the past being to produce materials with adequate strength, and high wear resistance and polishability retention. The more recent research and development efforts have addressed the issue of polymerization shrinkage and its accompanying stress, which may have a deleterious effect on the composite/tooth interfacial bond. Current efforts are focused on the delivery of materials with potentially therapeutic benefits and self-adhesive properties, the latter leading to truly simplified placement in the mouth. **Significance:** There is no one ideal material available to the clinician, but the commercial materials that comprise the current armamentarium are of high quality and when used appropriately, have proven to deliver excellent clinical outcomes of adequate longevity.

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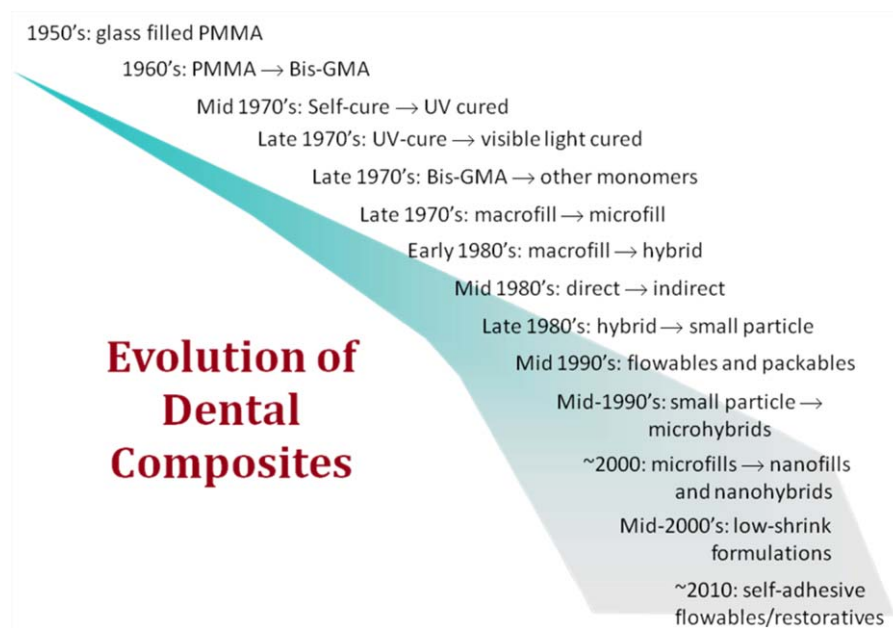


Fig. 1 – A perspective on the evolution of dental composites.

## 1. Introduction

The composition of resin-based dental composites has evolved significantly since the materials were first introduced to dentistry more than 50 years ago (Fig. 1). Until recently, the most important changes have involved the reinforcing filler, which has been purposely reduced in size to produce materials that are more easily and effectively polished and demonstrate greater wear resistance. The latter was especially necessary for materials used in posterior applications, but the former has been important for restorations in all areas of the mouth. Current changes are more focused on the polymeric matrix of the material, principally to develop systems with reduced polymerization shrinkage, and perhaps more importantly, reduced polymerization shrinkage stress, and to make them self adhesive to tooth structure. Several articles recently have reviewed the current technology of dental composites [1,2] and described future developments, such as self-repairing and stimuli-responsive materials [3]. The current review will provide a brief historical perspective on dental resin composites to serve as a framework for a treatise on the current state of the art, primarily concentrating on work published in the past 5 years.

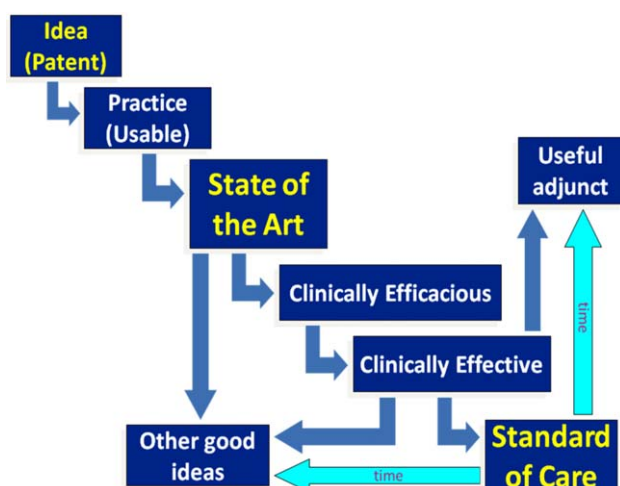
Resin composites are used for a variety of applications in dentistry, including but not limited to restorative materials, cavity liners, pit and fissure sealants, cores and buildups, inlays, onlays, crowns, provisional restorations, cements for single or multiple tooth prostheses and orthodontic devices, endodontic sealers, and root canal posts. It is likely that the use of these materials will continue to grow both in frequency and application due to their versatility. The rapidity by which the materials have evolved suggests a constantly changing state of the art.

The state of the art is defined as “the level of development (as of a device, procedure, process, technique, or science)

reached at any particular time usually as a result of modern methods.” (Mirriam Webster Dictionary) When discussing patentable ideas, this has been more precisely defined (European Patent Convention) as “[the] state of the art shall be held to comprise everything made available to the public by means of a written or oral description, by use, or in any other way, before the date of filing of the European patent application.” Thus an idea may be based on prior art, but only is considered to be new if it does not form part of the current state of the art. Thus, the state of the art is constantly in flux. Further, the state of the art is usually distinguishable from what might be termed the “standard of care,” or the material/technique that generally has been adopted by the profession for a specific purpose.

This difference between state of the art and standard of care is made more evident when one examines the development of dental composites and follows the path of a new material (Fig. 2). When a new dental composite material is conceived by an individual or a company, a patent application is typically filed to protect the concept. At the same time, or at some time in the future, the concept is reduced to practice, providing a material that has application for a specific purpose or set of purposes. The material comprises a portion of the current state of the art by virtue of its publication or presentation to the profession. However, the material must proceed through a more elaborate path to be considered a part of the current standard of care. In the ideal process, this requires a demonstration that the material is clinically efficacious. In other words, it must be shown to be used successfully in a controlled situation, such as a clinical trial. However, as has been seen many times, there is no guarantee that such a material will be shown also to be clinically effective when provided to all general practitioners for general use.

A material cannot achieve the level of standard of care, as defined by “the degree of care or competence that one is expected to exercise in a particular circumstance or role,”



**Fig. 2 – The pathway through the state of the art toward building the standard of care.**

(Merriam-Webster's Dictionary of Law) until it has been broadly accepted by the profession for its intended purpose(s). If efficacy and/or effectiveness cannot be proven for the new composite, then it may simply fade into history as many "other good ideas." If the material does prove to be effective, it may still not become the standard of care, perhaps because there are better options available that are easier to use, of lower cost, or have some other benefit. The material may simply then become a useful adjunct to the current standard of care. The standard of care is also fluid, and a material that was the standard may simply with time relapse to becoming a useful adjunct or just another good idea. Thus, the state of the art and the standard of care are likely to be very different. This is emphasized by the fact that the time from which a new idea/practice option is introduced to when it becomes accepted by the majority of dental practitioners may be more than 10 years [4].

Describing the state of the art in dental composites requires a discussion of the formulation of current materials and the potential for future developments, the properties and limitations of the currently marketed products, and the important considerations for their clinical use. This manuscript will discuss each of these issues.

## 2. Dental composite formulation

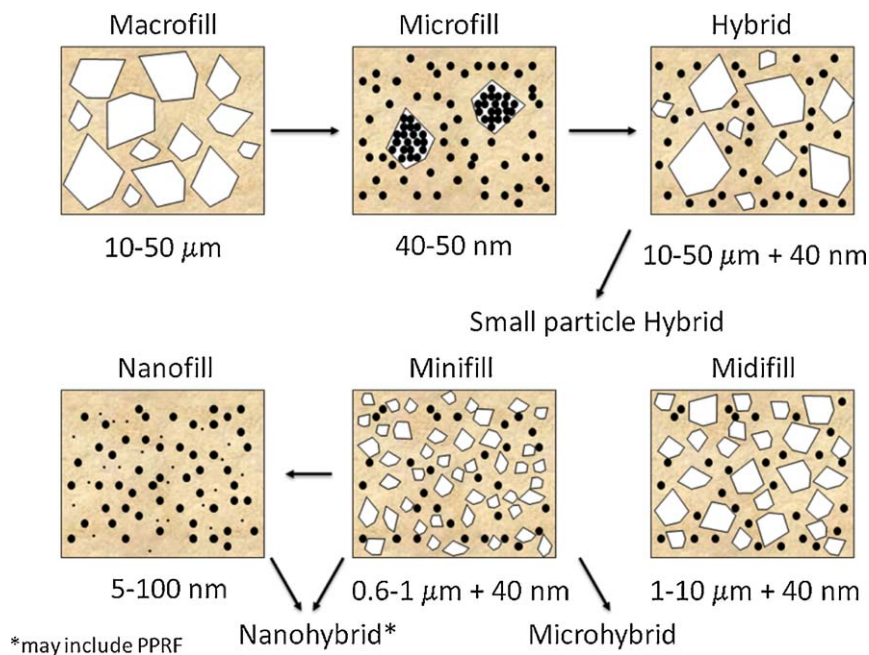
### 2.1. Types of dental composites and their development

Dental composites can be distinguished by differences in formulation tailored to their particular requirements as restoratives, sealants, cements, provisional materials, etc. These materials are similar in that they are all composed of a polymeric matrix, typically a dimethacrylate, reinforcing fillers, typically made from radiopaque glass, a silane coupling agent for binding the filler to the matrix, and chemicals that promote or modulate the polymerization reaction. The many types of fillers in use recently have been reviewed [1]. The predominant base monomer used in commercial dental

composites has been bis-GMA, which due to its high viscosity is mixed with other dimethacrylates, such as TEGDMA, UDMA or other monomers [5]. Some of these monomers, or modified versions of them, also serve as base monomers in many commercial materials. While there have been attempts to develop different polymerization promoting systems, most composites are light-activated, either as the sole polymerization initiator or in a dual cure formulation containing a chemically cured component. The most common photoinitiator system is camphoroquinone, accelerated by a tertiary amine, typically an aromatic one [6]. Some commercial formulations have included other photoinitiators, such as PPD (1-phenyl-1,2-propanedione) [7], Lucirin TPO (monoacylphosphine oxide), and Irgacure 819 (bisacylphosphine oxide) [8], which are less yellow than CQ and thus potentially more color stable. Additional photoinitiators, such as OPPI (p-octyloxy-phenyl-phenyl iodonium hexafluoroantimonate) have been proposed based on encouraging experimental results [9].

The different types of composite materials are distinguished by their consistency. The universal restorative capable of being placed with a syringe or instrument may have a variety of consistencies depending upon its formulation. These materials are distinguished from the flowable composites, designed to be dispensed from very fine bore syringes into tight spaces for enhanced adaptation, and from the packable composites, designed to provide significant resistance to an amalgam condenser or other instrument in order to avoid slumping and to enhance the formation of tight interproximal contacts. Flowable composites are typically produced with a lower viscosity by reducing the filler content of the mixture, or by adding other modifying agents, such as surfactants, which enhance the fluidity while avoiding a large reduction in filler content that would significantly reduce mechanical properties and increase shrinkage [10]. Packable composites achieve their thicker consistency through modification of the filler size distributions or through the addition of other types of particles, such as fibers, but generally not by increasing overall filler level [11].

Within each type of composite, the materials are further distinguished by the characteristics of their reinforcing fillers, and in particular their size (Fig. 3). Conventional dental composites had average particle sizes that far exceeded  $1\ \mu\text{m}$ , and typically had fillers close to or exceeding the diameter of a human hair ( $\sim 50\ \mu\text{m}$ ). These "macrofill" materials were very strong, but difficult to polish and impossible to retain surface smoothness. To address the important issue of long-term esthetics, manufacturers began to formulate "microfill" composites, admittedly inappropriately named at the time, but probably done to emphasize the fact that the particles were "microscopic". In truth, these materials were truly nanocomposites, as the average size of the amorphous spherical silica reinforcing particles was approximately  $40\ \text{nm}$ . The field of nanotechnology is defined at the nanoscale, and includes the  $1\text{--}100\ \text{nm}$  size range. Thus, the original "microfills" would have more accurately been called "nanofills", but likely were not due to the lack of recognition of the concept of "nano" at the time. The filler level in these materials was low, but could be increased by incorporating highly filled, pre-polymerized resin fillers (PPRF) within the matrix to which additional "microfill" particles were added.



**Fig. 3 – The chronological development of the state of the art of dental composite formulations based on filler particle modifications.**

The “microfill composites were polishable but generally weak due to their relatively low filler content, and a compromise was needed to produce adequate strength with enhanced polishability and esthetics. Therefore, the particle size of the conventional composites was reduced through further grinding to produce what was ultimately called “small particle hybrid” composites. These were further distinguished as “midfills,” with average particle sizes slightly greater than  $1\mu\text{m}$  but also containing a portion of the 40 nm-sized fumed silica “microfillers.” Further refinements in the particle size through enhanced milling and grinding techniques resulted in composites with particles that were sub-micron, typically averaging about  $0.4\text{--}1.0\mu\text{m}$ , which initially were called “minifills” [12] and ultimately came to be referred to as “microhybrids.” These materials are generally considered to be universal composites as they can be used for most anterior and posterior applications based on their combination of strength and polishability. The most recent innovation has been the development of the “nanofill” composites, containing only nanoscale particles. Most manufacturers have modified the formulations of their microhybrids to include more nanoparticles, and possibly pre-polymerized resin fillers, similar to those found in the microfill composites, and have named this group “nanohybrids.” In general, it is difficult to distinguish nanohybrids from microhybrids. Their properties, such as flexure strength and modulus, tend to be similar, with the nanohybrids as a group being in the lower range of the microhybrids, and both being greater than microfills [13,14]. While some have shown evidence for reduced stability during water storage for nano-hybrid or nano-fill composites vs. microhybrids [15], others have shown an opposite trend [16] or fairly similar susceptibility to aging [17]. It has been suggested that the slightly lower properties of some nanohybrid composites may

be due to the incorporation of pre-polymerized resin fillers [18]. Regarding clinical evaluations, two recent studies over 2 and 4 years, respectively, showed similar excellent results in class II cavities for a nanofill vs. a microhybrid [19] and nanohybrid vs. a microhybrid, with slight evidence for better marginal integrity for the micro-hybrid in the latter study [20].

## 2.2. Composition of current composites

The state of the art of the composition of dental composites has been changing rapidly in the past few years. The nanofill and nanohybrid materials represent the state of the art in terms of filler formulation [1,2]. Comprehensive electron microscopy and elemental analysis has been performed on many current composites to verify the significant differences in filler composition, particle size and shape [21]. New options for reinforcing fillers generally have focused on nanosized materials and hybrid organic-inorganic fillers [1]. Years ago, novel organically modified ceramics (ORMOCERS) were developed [22] and have been used in commercial products. However, significant progress has been made in the development of new monomers for composite formulations with reduced polymerization shrinkage or shrinkage stress, as well as those with self-adhesive properties.

The epoxy-based silorane system used in Filtek Silorane LS (3M ESPE) [23], provides verified lower shrinkage than typical dimethacrylate-based resins, likely due to the epoxide curing reaction that involves the opening of an oxirane ring. This commercial composite has been shown to have good mechanical properties [15,24]. In one clinical study, the marginal quality of the silorane composite was shown to be somewhat inferior to that of a nanohybrid composite [25]. Perhaps this is not surprising in that contraction stress, and not contraction itself, is considered to be the

more important phenomena, and it has been shown that Silorane LS does not produce lower contraction stress than other composites [26]. Others have experimented with other monomers, such as tetraoxaspiroundecane (TOSU), added to silorane systems and showed stress reduction, but the reduced stress may also be due in part to a reduction in mechanical properties [27].

Other monomers with increased molecular weight have been developed for composites with reduced shrinkage. The modified urethane dimethacrylate resin DX511 from Dupont found in Kalore (GC) is said to reduce shrinkage due to its relatively high molecular weight compared with bis-GMA and traditional UDMA (895 g/mole vs. 512 g/mole vs. 471 g/mole, respectively). The urethane monomer TCD-DI-HEA found in Venus Diamond (Kulzer) has been shown to produce lower polymerization contraction stress than other composites marketed as low-shrinking [26]. The dimer acid monomers used in N'Durance (Septodont) are also of relatively high molecular weight, i.e. 673–849 g/mole, and have been shown to have high conversion of carbon double bonds while undergoing lower polymerization shrinkage than bis-GMA-based systems [28,29].

The latest trend has been toward the development of flowable composites containing adhesive monomers, such as Vertise Flow (Kerr) and Fusio Liquid Dentin (Pentron Clinical). These formulations are based on traditional methacrylate systems, but incorporating acidic monomers typically found in dentin bonding agents, such as glycerolphosphate dimethacrylate (GPDM) in Vertise Flow, which may be capable of generating adhesion through mechanical and possibly chemical interactions with tooth structure. These materials are currently recommended for liners and small restorations, and are serving as the entry point for universal self-adhesive composites.

### 2.3. Future developments

A recent review noted that efforts to modify fillers have been aimed at improving the properties of composites by the addition of polymer nonofibers, glass fibers, and titania nanoparticles [2]. There is also very interesting work incorporating silsesquioxane nanocomposites which are essentially an organic-inorganic hybrid molecule that reduce shrinkage, but also reduce mechanical properties if used in too high of a concentration [30]. Perhaps the most promising work in composites with modified fillers for both enhanced mechanical properties and remineralizing potential by virtue of calcium and phosphate release has been the work with fused silica whiskers and dicalcium or tetracalcium phosphate nanoparticles [31,32]. These composites may be stronger and tougher, but the optical properties are not ideal and their opacity requires them to be self-cured or heat-processed at this point. Calcium fluoride containing fillers also have been added to filled dental resins and have shown high fluoride release and good mechanical properties [33]. There are other monomers that are in various stages of development for potential use in dental composites, such as the (meth)acrylate vinyl ester hybrid polymerization system which exhibits phase separation during curing [34], thiolene monomers [35], multimethacrylate derivatives of bile acids, and others [36–39].

It is expected that universal restorative materials based on the self-adhesive monomers being used or proposed in the flowable systems also will be forthcoming.

Other areas of development have included the incorporation of anti-bacterial agents and remineralizing agents into composites. Examples of compounds that have been added to resin composites to kill bacteria or inhibit biofilm formation include fluoride [32,33], chlorhexidine [40], zinc oxide nanoparticles [41], quaternary ammonium polyethyleneimine nanoparticles [42], and MDPB monomer [43]. The effectiveness of the various fluoride-releasing restorative materials have been critically reviewed, and it was concluded that the clinical results are not conclusive for dental restorative materials, including composites [44]. Remineralization may be promoted by the slow release of calcium and phosphate ions followed by the precipitation of new calcium-phosphate mineral [32,33]. Years ago a material was developed which was purported to exhibit “smart release” of these ions as a result of an acidic challenge, as occurs during caries formation. This material, Ariston pHc, was not ultimately successful, in large part due to the fact that it absorbed too much water which affected its dimension and properties. But the idea of a “smart” material that reacts to its environment to release remineralizing ions or anti-microbial agents is attractive and still a focal point of research.

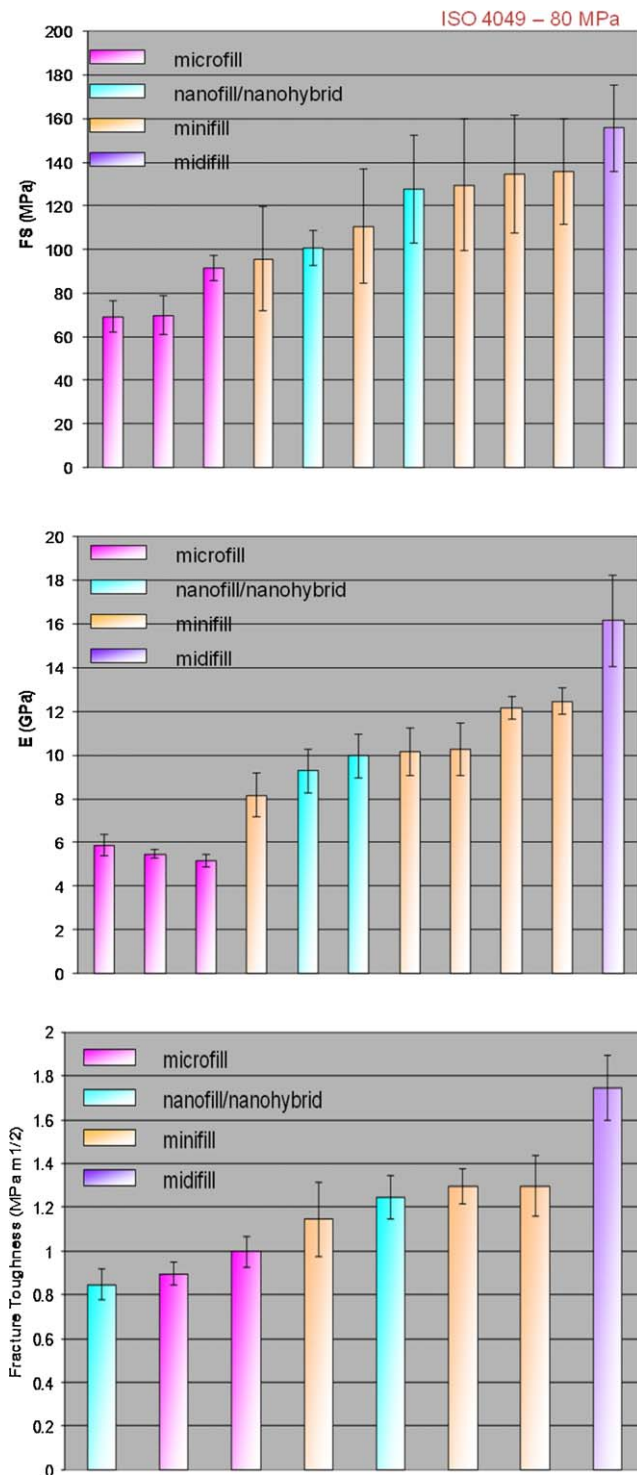
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## 3. Properties of dental composites

### 3.1. Current materials

Current dental composites have adequate mechanical properties for use in all areas of the mouth. But concern still exists when the materials are placed in high stress situations, especially in patients with bruxing or parafunctional habits. The concern here is for fracture of the restoration as well as wear. Wear is considered to be a lesser problem for current materials as compared to those that were the standard of care a decade ago, in large part due to refinement in the size of the reinforcing fillers which significantly reduced the magnitude of abrasive wear. However, when placed in large preparations, perhaps on several teeth in a quadrant, and when used to replace cusps, the wear of these materials still warrants attention [20].

Nearly exhaustive datasets on the mechanical properties of dental composites have been presented in recent years, and these informative articles can be consulted for more specific information [13–15]. In the author's lab, various brands of materials have been evaluated (Figs. 4–6). The data provides an opportunity for an overall view of the relative magnitude of the properties for the different composites types, and generally show that mechanical properties are mostly related to filler content, with the composites having the most filler being the strongest (Fig. 4), stiffest (Fig. 5), and toughest (Fig. 6). This is not surprising, as this trend is predicted by the rule of mixtures for composite materials. However, it is instructive to compare the mechanical properties of dental composites to other dental restorative materials. In general, dental composites have similar flexure strength, fracture toughness and tensile strength as porcelain and amalgam, and are superior to



**Figs. 4–6 – Comparison of the flexure strength, flexure modulus and fracture toughness of representative commercial composites.**

glass ionomers. Perhaps the property in which dental composite is most conspicuously deficient in comparison to amalgam is elastic modulus, where composite is typically several times lower. This lower modulus may allow enhanced deformation and dimensional change on occlusal surfaces under high stress which lead to defect formation or enhanced wear due to increased surface contact.

### 3.2. Future enhancements

Improvements in the properties of dental resin composites are constantly being sought. The target mechanical and physical properties are difficult to define because there is currently little correlation between the properties of composites and their clinical performance. However, given that secondary caries and fracture are the two primary reasons given for replacement of dental composites [45], it is warranted to continue to pursue improvements in strength and toughness, as well as shrinkage and its accompanying stress. The target shrinkage level is likely somewhere greater than zero to allow room for expansion due to water sorption. Current resin systems are not completely hydrophobic. The extent of water uptake is dependent upon the monomer formulation, and a recent study has shown lower water uptake for silorane-based systems [46]. But as new formulations are designed to be self-adhesive, they will most likely be even more hydrophilic than current resins. Thus, a shrinkage level between 0.5% and 1.0% by volume would seem to be a reasonable target, and some systems already are at or near this level.

Regarding strength and toughness, current materials are nearly as strong (flexure, compression and tension) as dental amalgams and porcelain, but less strong than “high-strength” ceramic systems and casting alloys. This is significant, in that casting alloys for PFMs and the high strength ceramics, such as those used as substructures for dental restorations, typically do not fail by bulk fracture. Rather, the veneering porcelain chips or delaminates [47], which is consistent with its generally low strength. Thus, because amalgams and porcelains do fracture, and they have similar strength as dental composite, it is likely that flexure strength of several hundred MPa, equivalent to that of the high strength ceramics, would be most ideal. This is not an easy challenge, and even the inclusion of high strength whiskers into heat-cured dental resins has only increased the flexure strength of highly filled composites to a little over 200 MPa [48]. Fracture toughness is another important property, and may correlate with intraoral chipping of surfaces and margins [49,50]. The best current composites have fracture toughness below  $2.0 \text{ MPa m}^{1/2}$ , which is similar to amalgam and better than porcelain. However, higher strength ceramics have fracture toughness that are 2–3 $\times$  as great, and this may be a reasonable target for dental composites based on the statements made above with respect to strength and fracture. Again, fiber or whisker reinforcement has produced very significant enhancements in toughness [48], but not to the range of high toughness ceramics or casting alloys, and this may be what is required to render the materials essentially fracture resistant under all oral conditions.

## 4. Important clinical considerations

### 4.1. Placing dental composites

The primary reason for the clinical replacement of dental composites is secondary caries, followed by fracture [45]. The former is proposed to be related to the polymerization shrinkage and shrinkage stress created on the interfacial bond, as

well as the durability of this bond, and on the quality of the placement of the restoration. The latter is due to limitations of the mechanical properties of the materials, as well as to issues related to cavity design, amount and quality of supportive tooth structure, and the specific occlusion.

Layering is the standard of care for placement of dental composites in cavity preparations exceeding 2 mm. This procedure is based on the desire to ensure as complete a cure as possible by virtue of sufficient exposure of the entire increment to the curing light, as well as to reduce the volume of contracting material to mitigate to some extent polymerization shrinkage stresses. Various techniques have been proposed in the literature [51,52] and many variations on the theme can be expected. The bulk curing of composite, considering that ample light energy was able to be transferred to the material, has been suggested for large preparations, but the evidence seems largely against this approach due to concerns over elevated stress generation and tooth deformation [53]. However, it is important to note that little if any strong clinical data exists to support one particular composite application method over another. In fact, though polymerization shrinkage and its associated stress are presumed to affect marginal integrity and clinical performance, there is not definitive clinical data to support this hypothesis [45,54].

Due to concerns over post-operative sensitivity and achieving and maintaining adhesion to dentin, dental composite restorations are often lined with glass ionomers or flowable composites. Clinical evidence for enhanced longevity of class II composites with resin modified glass ionomer liners vs. adhesive bonding exists [55], but there also is evidence for enhanced performance of class II composite restorations relying solely on adhesive bonding in the proximal area [56]. A recent study conducted in a university setting showed no difference in performance for lined vs. unlined posterior composites, though the authors noted that results in general practice may not be predicted by this clinical evaluation model [57]. It is fair to say that at this time, both methods for restoring class II composites represent the standard of care.

The other important aspect with respect to placement of dental composites relates to their handling characteristics. This is evident in the way in which the practitioner has embraced flowable composites, and the number of publications assessing handling properties of all types of composites, such as rheology [58–60], slumping [61–63], and stickiness [64,65], and the development of test methods to assess these subjective qualities. The viscosity is a property that is most important for flowable composites, and studies show that viscosity varies greatly among brands, without a correlation to filler particle shape and only a weak correlation to filler volume that does not hold within a specific type of composite, i.e. within flowables [58,60]. However, composites are pseudoplastic, or shear-thinning materials, meaning that they become more fluid when placed under greater shearing forces, such as during placement with a syringe. The slumping resistance of the composite is related to viscosity, but is more complex. A slumping resistance index (SRI) has been estimated using an imprint method for three commercial composites and shown to be related to shear flow resistance, with a nanofill composite having a higher SRI than two microhybrids [61]. In

another study, the slumping resistance of flowable composites also was shown to be related to the complex viscosity, as one might expect [63]. Significant variation in slumping tendency has been shown for four commercial materials by measuring of the deformation of an uncured composite cast made from an impression [62]. Another subjective characteristic of composites is stickiness. An attempt has been made to quantitate stickiness by measuring the force exerted against a plunger as it is removed from a composite mass [64]. Three commercial composites have been tested by placing steel, dentin and bonded dentin to the bottom of the probe to measure stickiness to these various surfaces. [65]. Stickiness was highest against dentin and lowest on bonded dentin, and tended to increase as the temperature was increased from 23 to 37 °C.

#### 4.2. Finishing, polishing and repairing

The finish and polish attainable on dental resin composites is to some extent a function of their composition, with some materials demonstrating a preference for certain polishing methods [66–68]. In the past, fine particle disks provided the best overall surface finish and gloss for most composites, but more recent studies suggest that while the use of successively finer disks are still very effective, recently developed two- and one-step systems may be slightly better at producing the highest gloss for most types of dental composite [66,69]. Most clinicians will admit that the high initial shine may be important to the patient, especially for the anterior teeth, but the main concern of the dentist is the surface quality after months and years of service. One guideline suggests that a gloss level of 40% is the minimum acceptable clinically [69]. All composites will roughen with time as the surface is exposed to the erosive and abrasive effects of food, drink, and other things. Studies examining the polish retention show a difference in the maintenance of surface quality based on the filler particle size, with roughness and gloss tending to increase with particle size, though this is dependent upon brushing load and time [70,71]. Some composites, specifically nanofills and microfills, may show a reduction in gloss during toothbrushing experiments, while microhybrid composites typically show an increase in gloss after the initial stages of brushing, followed by maintenance of a steady state or slight reduction [72]. This differs from surface roughness, which typically increases for all types of composites during brushing, but to different extents. The differences are most likely significant in terms of surface shine, and less important from the standpoint of plaque retention. When exposed to toothbrushing in experiments, most nano-hybrid and micro-fill composites maintain a surface roughness below 0.2  $\mu\text{m}$ , which is considered to be the threshold for plaque retention [73]. Further, though there is a strong correlation between surface roughness and surface gloss, gloss has been shown to be the more sensitive characteristic for measuring the retention of surface quality after brushing [70,71].

The repair of resin dental composites is an important feature, and one that has only recently been investigated through formal studies. The limited body of work in this area was the subject of a recent review [74]. While the review notes that there is a deficiency in randomized controlled



trials of composite repair, it does point out that recent clinical studies of 2–3-year duration have shown good outcomes for repairs or resealing of marginal defects in composites [75–77]. The most recent article describes a 7-year recall and reinforces the success of this conservative intervention strategy [78]. In a recent survey of general practitioners, one half stated that they would repair a composite restoration with a defective margin in enamel, though most would replace the restoration if the defective margin was on dentin [79]. These results suggest that repair of composite restorations with defective margins in enamel is considered state of the art, and that it may be becoming the standard of care.

The conservative nature of repairing chips, defects, stains, etc. has long been recognized as desirable, but in some cases has been considered to be a compromise in terms of the overall quality and longevity of the restoration. The repair method has improved little over the years, being predominantly an exercise in attaining strong mechanical adhesion to the aged surface. Attempts to expose and bond with residual methacrylate groups have been presented, but there is little evidence that this aspect of bonding is significant or superior to mechanical adhesion. Mechanical bonding is achieved by roughening the intra-oral surface through air abrasion, phosphoric acid application to clean the surface of debris and etch any available enamel, application of a thin layer of unfilled resin for enhanced adaptation to the roughened surface, followed by placement of the resin composite of choice. Recent studies also suggest that air abrasion combined with silica coating (and possibly silane) is a very effective preparation method for composite repair [80,81]. The use of intermediary unfilled resins that are more hydrophobic tend to show superior bond stability [82]. Efforts to enhance the bond through hydrofluoric acid application to “etch” fillers or applying silane coupling agents to bond to exposed fillers have largely been shown to be ineffective in laboratory studies, and are thus not recognized as the standard of care [80].

#### 4.3. Clinical outcomes

The current status of dental composites as anterior restoratives is the material of choice for most restorations. Clinical studies show good outcomes with few limitations, aside from some concerns over marginal staining (more a problem of the adhesive than the material), discoloration, and edge chipping in high stress situations. In anterior teeth, and especially for class V lesions, composite is the clear material of choice among general practitioners [83]. As a posterior restorative, resin composite is now the primary choice in many countries. Clinical studies show good performance, with some studies providing outcomes from 10 to 20 years showing relatively low annual failure rates of approximately 2% [84–86]. The overall consensus seems to be that composite has a slightly shorter longevity than dental amalgam when compared in the same study [87–89]. However, a recent study challenges this assumption in a 12-year evaluation of composites and amalgam, in which large composites showed a higher survival than amalgam in a low caries risk group, and the two materials showed equivalent survival in a high caries risk group [90]. Not surpris-

ing, both materials show higher failure rates in high caries risk patients.

## 5. Final thoughts and perspectives

Dental composites are versatile materials whose usage has continued to grow since their introduction to the profession over 50 years ago. The expanded use of these materials in a wide range of applications puts great demands on their properties and performance. This demand requires an ongoing investment in research and development and is evidenced by continuous introduction of new products to the market. While the state of the art of dental composites is very fluid and represents an abundance of options for the clinician, the standard of care is in general much more stable. This is logical in that the savvy practitioner likely demands some level of clinical proof before choosing to make a significant change in their practice behavior. This should be true for all dental restorative selections. Expectations are that further development of these materials will include enhancements in strength and fracture resistance, reductions in polymerization shrinkage and its associated stress, adhesion to tooth surfaces without special surface preparations or the application of separate bonding resins, the inclusion of antibacterial agents and/or compounds capable of enhancing their remineralizing potential, and designed responsiveness to the changing oral environment.

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