QUANTITATIVE COMPARISON OF INTERNAL ADAPTATION BETWEEN BULK-FILL AND TRADITIONAL MULTI-INCREMENT-FILL RESIN-BASED COMPOSITE MATERIALS

by

Fatema Sabri Alqudaihi

Submitted to the Graduate Faculty of the School of Dentistry in partial fulfillment of the requirements for the degree of Master of Science in Dentistry, Indiana University School of Dentistry, 2015.

Thesis accepted by the faculty of the Department of Restorative Dentistry, Indiana University School of Dentistry, in partial fulfillment of the requirements for the degree of Master of Science in Dentistry.

Anderson Hara

Tien-Min Gabriel Chu

Marco C. Bottino

Jeffrey A. Platt
Chairman of the Research Committee

Norman Blaine Cook
Program Director

Date

DEDICATION

First, I would thank Allah (SWT) for his continuous guidance and blessing.

My humble effort is dedicated to my deceased grandmother, for her love and prayers of day and night; to my loving parents, Sabri and Fathiea, whose affection, love, encouragement, and support make me able to get such success and honor; to my husband, Ahmed, whose words of encouragement and push for tenacity ring in my ear; to my kids, Faris and Sulaf, for their patience, smiles, and for making my life more meaningful and valuable.

I also dedicate this thesis to my sisters, brothers, aunts, cousins, and uncle, who were a great source of motivation, inspiration, and support throughout the entire process.

May God bless them all.

ACKNOWLEDGMENTS

It was a great experience and privilege to complete my MSD in the division of Dental Biomaterials, Department of Restorative Dentistry, Indiana University School of Dentistry.

I would like to convey my deepest gratitude to Dr. Nadia Shumayrikh, the head of the Dental Department at Qatif Central Hospital, for her unlimited support and encouragement to continue my graduate studies.

I would like to express the deepest appreciation to my mentor, Dr. Jeffrey Platt, and to my committee members: Drs. Anderson Hara, N. Blaine Cook, Tien-Min Gabriel Chu, and Marco C. Bottino for their help. Without their guidance, this thesis would not have been possible.

I would like to express my sincere thanks to Dr. Afnan Al-Zain, Clif Duhn, Ding Li, Jeana Aranjo, Judy Haines, and Adam Kelly for providing laboratory support throughout the project. I would like to thank George Eckert and Elizabeth Moser for help in the statistical analysis.

Special thanks go to my best friend, Dr. Ghaida Alyahya for her truthful feelings and support. Additionally, I offer regards to all my friends and to all who supported me during the completion of my project and thesis.

Lastly, I am heartily thankful for my family's unconditional love, encouragement, and unlimited support.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

INTRODUCTION

Given their numerous advantages, resin-based composite (RBC) materials have been widely used in dentistry since their development in the late 1950s. Besides having esthetic properties that mimic those of natural teeth, this type of restorative material does not require the removal of healthy tissues to achieve retention. RBC can be bonded to tooth structure using resin adhesives. As a result, RBC has several indications: direct filling of anterior and posterior caries lesions and tooth defects, esthetic bonding, and occlusion adjustments, as a luting cement for indirect restorations, and the bonding of orthodontic brackets.[1]

One reason for RBC restoration failure is post-operative pain or sensitivity. The hydrodynamic theory proposes that any change in fluid pressure and fluid movement stimulates pain receptors in the pulp that would cause post-operative pain and sensitivity following placement of resin composite restorations.[2] Any poor internal adaptation of a resin composite restoration will create gaps between the material and the tooth structure and allow fluid collection. This fluid will move under pressure changes, created during mastication or temperature change, into the dentinal tubules, and the patient will feel pain accordingly.[3] Another reason for RBC restoration failure is material loss as a result of gap formation, and inadequate internal adaptation that has an impact on the restorative material retention. Thus, internal adaptation of RBCs is a significant factor that could affect the long-term performance of the material.[3]

Many factors influence the quality of adaptation of RBC restorations, which are related to the material properties, cavity preparation, and operative technique. However,

polymerization shrinkage, and its associated stress, are some of the most adverse properties of the currently available materials.[3]

Many clinical techniques have been introduced to minimize the shrinkage stress and thereby reduce gap formation, such as control of the curing light intensity,[4] indirect placement of resin restorations,[4] application of a flowable resin liner,[5] and incremental layering techniques.[4] However, no method has been shown to be totally effective in abating the effects of polymerization shrinkage.[6]

One recommended technique is the incremental or layering technique, considered the standard way to eliminate gap formation and achieve an adequate bonding of composite to tooth structure.[6,7] The technique involves building up the restoration in multiple increments. Each increment is placed to a specific thickness in an oblique manner, and polymerized separately. Thus, the technique allows adequate light penetration to cure the material.[8] Moreover, it increases the unbonded surface area for RBCs relative to the bonded surface area and thus minimizes the C-factor (the ratio of bonded surface to unbonded free surface).[6,9] However, this technique has some drawbacks, such as increased chair time and inclusion of voids between the increment layers.[6]

Many efforts have been made to develop RBC materials that can fill the deep cavity all at once, utilizing a bulk-fill technique without affecting long-term performance. Unlike traditional RBCs, which typically are placed in increments of not more than 2-mm thickness, bulk-fill RBCs are intended to be placed in 4-mm, or sometimes greater, increments.[8] Given that all the restorative material is placed in one step, this technique could be easier, save time, and result in fewer voids in the bulk of the material.

The concept of a ‘‘bulk-filling’’ technique is not a new idea[10] and has been evaluated several times in the literature.[3,11-13] Historically, many disadvantages of bulk-filling preparations with light-cured composites are documented: the inability to effectively cure composite to depths more than 2 mm,[14,15] challenges related to the C-factor and the cavity design,[16,17] and potential complications due to the material shrinkage and increased gap formation.[16,18,19]

The major challenge facing the bulk-fill RBCs is their ability to be cured well in-depth. While the external surface of the composite is sufficiently cured, the material may not polymerize well in deeper portions.[20] Inadequately polymerized composite has been shown to be cytotoxic and could affect the longevity of the restoration negatively, including the internal adaptation to cavity walls.[21]

Over the past two decades, many manufacturers have introduced RBC materials that are claimed to have increased depth of cure and decreased polymerization shrinkage and gap formation, which would lend the materials to a bulk-fill placement technique. Recently, some of these products have gained popularity, and many studies have been done to test different aspects of their properties.[8] Multiple studies indicate comparable physical and mechanical properties among bulk-fill and increment-fill composite materials.[15,20,22] Furthermore, several manufacturers claim that bulk-fill materials have greater depth of cure, and lower polymerization-induced shrinkage stress than the traditional incremental-fill materials.[23,24] However, further investigation of the internal adaptation between the restorative material and the tooth structure is needed.

Bulk-fill restorative material products can be considered viable alternatives to the traditional incremental-fill materials, when placed into a preparation having a high C-

factor design, if high depths of cure are seen with less internal stress. As a result, reduced polymerization stress would decrease the incidence of gap formation, and accordingly, result in better internal adaptation, compared with traditional incrementally placed composites.[25]

OBJECTIVES

The aims of this study were to quantitatively evaluate the internal adaptation among different bulk-fill RBC materials and a traditional RBC placed incrementally by measuring the gap area between the restorative material and the tooth structure, and to evaluate aging effect on the internal adaptation.

HYPOTHESES

Null Hypotheses

1. There is no significant difference in the internal adaptation among bulk-fill RBC materials and a traditional RBC placed incrementally.
2. There is no significant difference in the internal adaptation among bulk-fill RBC materials and a traditional RBC placed incrementally in not-aged material compared with aged material.

Alternative Hypotheses

1. There is significantly better internal adaptation in a traditional RBC material placed incrementally compared with internal adaptation in bulk-fill RBC materials.
2. There is significantly better internal adaptation in a traditional RBC

material placed incrementally compared with internal adaptation of bulk-fill RBC material in not-aged material compared with aged material.

REVIEW OF LITERATURE

BACKGROUND

In modern dentistry, restoration requires balancing the functional, biological as well as esthetic properties of the material. The known early attempts to establish esthetic filling materials were based upon silicate cements. The silicates released fluoride, but experienced solubility as well as erosion. The problems with silicate materials resulted in the introduction of unfilled acrylic systems in the late 1940s and the early 1950s due to their being more tooth-like in appearance, easy to manipulate, insoluble in oral fluids, and relatively inexpensive.

In 1955 another important advance was made by Buonocore.[26] This was the development of micro-mechanical adhesion to the enamel of the tooth through phosphoric acid-etching creating microporosities in the enamel surface. The development of resin composites first occurred in 1962 and they have significantly evolved since then.[27]

RBC restorations are currently used for various applications in dentistry, which include but are not limited to applications such as cavity liners, restorative materials, and root canal posts. It is expected that the frequency of use as well as application of composite materials will be growing continuously due to their versatility.[28,29]

The demand by patients for tooth colored restorations instead of amalgam restorations has increased.[30] RBC materials have become the most preferred alternative to amalgam. According to Hickel and associates, the RBCs have been in use for many years, although they only started exhibiting improved wear resistance recently.[31-33] Roulet

actually noted that the average annual wear for new composites seems to be equal to that of amalgam.[34-37] Eakle and Ito observed in 1990 that one of the major challenges of resin restorations is microleakage.[38] According to Tyan and his associates the leakage can result from the polymerization shrinkage of resin material which creates a gap between the cavity walls and restoration.[39]

In recent years, dentin adhesives have successfully been developed with both hydrophilic groups and high wettability and this led to good results on the sealing of margins of Class II restorations being achieved.[40] The new adhesives have the ability to penetrate into a chemically conditioned dentin as well as to create a mechanical interlocking dependent on the formation of a hybrid layer as well as resin tags which penetrate into opened dentin tubules.[41-43]

Traditional dental adhesives of past generations utilized three steps which included: decalcification, infiltration and polymerization. The formation of an optimal hybrid layer requires the diffusion of a hydrophilic resin monomer mixture into the exposed collagen fibrils until the subsurface of demineralized dentin is reached.[44-53]

The clinical steps of bonding procedures might however be technique-sensitive and result in ineffective bonding if the operator is inexperienced.[42,50] Watanabe and his associates proposed self-etching primers so as to simplify handling properties, to reduce working time and to avoid the collapse of collagen fibrils.[54]

CLASSIFICATION OF RESIN-BASED COMPOSITE MATERIALS

According To Filler Particle Content

The development of new resin composites in the 1980s and the 1990s focused majorly on the size as well as the amount of filler particles.[55-61] The resin composites were categorized in three main groups according to filler content and they included: macrofilled, microfilled, hybrid, modern hybrid, and nanofilled composites (Table I).

Macrofilled Resin-Based Composites

Also known as conventional, this group had filler whose particle size was 10 μm to 40 μm. Their disadvantages included poor finish as well as relatively high wear. Quartz and strontium or barium glasses were among the most commonly used fillers in these composites. The quartz filler had good aesthetics and durability although it suffered from the absence of radiopacity as well as high wear of antagonist teeth. Although barium and strontium glass particles are radiopaque, they are less stable than quartz.

Microfilled Resin-Based Composites

These composites contain colloidal silica filler with a particle size of 0.01 μm to 0.05 μm. They were introduced in the late 1970s. The small particle size made it possible to polish the resin composite to achieve a smooth surface finish. However, the physical properties of the microfilled resin composites were not as good as that of macrofilled resin composites. Microfilled resin composites lacked of strength, bulk fractures were common, and they were undesirable for use in the high-stress areas.

Hybrid Resin-Based Composites

Hybrid composites (also called the original hybrid composites) were introduced in order to combine the advantages of both the macrofilled and the microfilled composites. They combined the small particles from microfilled composites with the stronger macrofilled composite particles as an attempt to create a more ideal material. The hybrid resin composites that were first introduced contained relatively large filler particles with a size of 15 μm to 20 μm together with colloidal silica with a particle size of 0.01 μm to 0.05 μm. Unfortunately, the hybrid composites failed to replace the microfilled composites due to their inferior esthetic properties and polish. Yet, they succeeded only in becoming a posterior material.

Modern Hybrid Resin-Based Composites

Modern hybrid composites (also called microhybrid composites) evolved from hybrid composites. The size of the largest particles in modern hybrid composites was decreased to be not more than 1 μm. Modern hybrid composites maintained the strength of the hybrid materials, but the esthetics have significantly improved. The modern hybrid composites also exhibited excellent physical characteristics and improved handling. Furthermore, they have proven successful for both anterior and posterior restorations.

Nanofilled Resin-Based Composites

They have recently been introduced in the market. They have filler particles whose sizes are less than 10 nm (0.01 μm). The nanofilled composites exhibited mechanical and physical properties similar to those of modern hybrid composites, but perform significantly better in terms of polish and gloss retention. Nanofilled composites

have demonstrated outstanding strength and wear properties, have good handling characteristics, and are highly esthetic.

According to Viscosity

Other classifications of RBCs include either the high-viscosity "packable" RBCs or low-viscosity "flowable" RBCs.

Packable Resin-Based Composites

The techniques of RBC are significantly more technically demanding than that of placing a Class II amalgam restoration. The development of acceptable proximal contours as well as contact can be quite challenging in various instances, although there may be need for not only special wedging techniques but also special wedging instruments. Products that are known as packable RBCs having improved handling characteristics were introduced so as to overcome such difficulties. The packable RBCs contain a high quantity of filler loading (about 80% by weight), which consequently enables them to be relatively easier to place as well as to be packed into the cavity and finally to be carved to form the shape that is required. One of the notable applications of the packable RBCs is the re-establishment of the teeth contour as well as proximal contacts.[62] It should be noted that the increase in the quantity of the filler particles to exceed the conventionally used quantity leads to porosity as well as the insufficient wetting brought about by the resin matrix on the particles. The packable RBCs high viscosity made them almost impossible to extrude via syringes with small bore or a delivery system of a unit-dose.[63] In the case of RBCs, the ability to stick to the cavity wall is preferred, although this is not the case when dealing with the dental instruments. Manufacturers eliminated the

stickiness by slightly varying the content of the filler as well as by employing varied matrix monomers in order to reduce the viscosity of the matrix. The enabled the material to have enough flow so as to adapt to the preparation of the cavity when packing.[63,64]

Flowable Resin-Based Composites

'Flowables' are low-viscosity composites which are obtained from formulations having a filler loading that is about 20 percent to 25 percent lower than that of the conventional composites.[65] They have a good wetting ability that favors their adaptation to the cavity walls, and therefore are expected to reduce the risk for air entrapment as well as void inclusion.[66,67] The flowable RBC material is relatively easier to use.[68] Furthermore, they have higher wettability of the surface of the tooth, easier penetration into irregularities, higher flexibility.[69,70] In addition, application of these flowable resin composite materials is important when restoring highly conservative preparations, the repair of margins of existing RBC restoration, the luting of porcelain veneers, the resurfacing of RBC or restorations of glass ionomer and the rebuilding of worn contact areas of RBC.[71,72] Furthermore, the flowable materials have the ability to absorb/break stress under conventional RBCs.[73]

RESIN-BASED COMPOSITE MATERIAL PLACEMENT TECHNIQUES

Different techniques have been used to facilitate marginal adaptation and to minimize the RBC restoration microleakage.[74]

Incrementally Placed Resin-Based Composites

When the RBCs are being polymerized, there is a competition between shrinkage stress and the adhesive-dentin bond, which has the ability to bring about failure of the bond, and consequently the failure of restoration. The inability of the adhesive to keep the RBC bonded to the structure of the tooth brings results into the formation of interfacial gap which has the ability to help in the post-operative sensitivity.[75]

The RBC material is placed within the cavity in 2-mm layers which are irradiated before the next layer is added until the completion of the cavity restoration.[76,77] The intention behind the incremental technique was to minimize the C-factor. C-factor is the "ratio of bonded surfaces of the restorations to the unbonded surfaces, and consequently, to relieve the polymerization shrinkage stresses developed at the bond interface between the tooth and the resin-composite."[78,79] The incremental placement of visible light-cured RBC has been taken to be an acceptable method that can be used in the provision of optimum contour, especially for restorations which are difficult to access.[77]

There are several disadvantages associated with the incremental layering technique that include higher probability for introducing porosity between different layers and a prolonged treatment session resulting in a relatively higher cost for the patient.

Bulk-Filling Resin-Based Composites

Restoring cavities, particularly deep ones having RBC increments of 2-mm layers, consumes a lot of time and leads to the increase in the risk of air bubble incorporation or contamination occurring between the increments. This concept is not new; it had been used with the chemically cured RBC materials when they were introduced to the market. Recently, some manufacturers introduced new types of light curable RBC materials,

which are referred to as the “bulk-fill” materials, and it is believed that they are curable to a 4-mm increment thickness.[80]

A number of researchers have conducted studies to investigate the physical as well as mechanical properties for various bulk-fill RBC materials and their results were quite encouraging. In one study, Czasch and Ilie examined parameters which included Vicker’s hardness, indentation modulus, flexural strength as well as flexural modulus.[15] The variety of RBCs under investigation were found to have values of hardness as well as polymerization shrinkage similar to those of incrementally placed RBCs.[80,81] In addition, there exist some brands of flowable bulk-fill RBCs which, when applied as bases under conventional RBCs, were shown to significantly minimize cuspal deflection during light irradiation.[82]

Although there are obvious advantages of filling all of a tooth preparation with composite at one time, the disadvantages associated with such practice are also apparent. The potential advantages that are associated with bulk-filling include the presence of fewer voids which may be present in the mass of the material due to the fact that all of it has to be placed at one time and the technique is relatively easier and faster than the one in which numerous increments are placed. However, some of the potential disadvantages that are associated with bulk-filling include the presence of more voids in the mass of the material because of the difficulty in controlling the mass placement, the challenges of making adequate contact areas in case the matrices that are used are not adequate, more pronounced shrinkage stress when bulk-filled as compared to when placed in increments because the whole mass polymerizes at once instead of in small increments, and polymerization inadequacy of the resin in the depth of the restoration.[20,83-85]

The first-generation flowable composites were not suitable for the full-depth posterior fillings due to their inferior mechanical properties as well as increased volumetric shrinkage when compared to conventional paste-like composites, mainly because of the lower filler content.[65,86] Thus, they could only be used as a liner or sealer, or in order to restore very small cavities.[65-67,86,87] As the dental industry continued searching for materials with improved properties, the current generation of flowable composites emerged containing higher filler content and are said to have increased mechanical properties. This has made them recommended for the restoration of larger posterior preparations.[88] To continue the simplification of the filling procedure (and also to save precious chair time), the current trend in composite technology includes the development of flowable restorative composites that may be placed in bulk up to a 4-mm thickness.[13,89,90]

BONDING OF RESIN COMPOSITES TO ENAMEL AND DENTIN

Introduction

Enamel is made up of 96-percent minerals, hydroxyapatite, $Ca_{10}(PO_4)_6(OH)_2$, which is packed in prisms, 1.0-percent organic material, and 3.0-percent water.[62] Buonocore illustrated that bonding resin to enamel after etching with phosphoric acid was very possible.[26] Approximately 10 μm of enamel is usually removed from the surface during etching and a very rough surface with porosities between 25 μm to 75 μm deep is created. Etching leads to the increase of the surface area more than 2000 times in addition to improving the surface energy as well as wettability of the enamel. This enables the resin to penetrate the micro-irregularities, which results in the formation of an intimate

micromechanical bond to exist between enamel and resin. Buonocore began the use of 85-percent phosphoric acid, but subsequent studies have demonstrated that etching with 20-percent to 50-percent phosphoric acid created the best bond strength to enamel.[26,91]

Dentin is made up of about 70-percent inorganic material (known as hydroxyapatite), 20-percent organic material (mainly collagen) and 10-percent water.[91,92] Although it is not homogenous, it also contains dentin tubules that traverse the whole of its thickness. The tubules contain a fluid that flows from the pulp to the surface, making the dentin hydrophilic. Consequently, the bonding of a hydrophobic resin to vital dentin is quite difficult. In 1982 Nakabayashi and his associates described the formation of the hybrid layer, which involved the penetration of hydrophilic monomers in acid-etched dentin.[93] In 1987 Fusayama introduced the total etch technique, which is a simultaneous conditioning of the whole cavity.[94]

Enamel-dentin bonding systems contain three components:

1. A conditioner in the acid form (such as maleic acid, phosphoric acid, EDTA).

2. A primer in the bifunctional/amphiphilic monomers form in suitable solvent(s). One of the most commonly used monomers is hydroxyethyl methacrylate (HEMA). The common solvents used include water, acetone, ethanol, or a mixture of these.

3. A bonding agent (also referred to as a sealer), which may be made up of a mixture of Bis-GMA and HEMA.

The conditioner is used so as to modify and/or remove the smear-layer as well as to demineralize the enamel surface and dentin hydroxyapatite. The collagenous network is uncovered in the dentin surface. The smear layer is mostly made up of coagulated

proteins and is usually highly contaminated with bacteria although it can have different thicknesses based on the preparation procedure. The primer will penetrate both demineralized enamel and dentin. In the dentin, the primer interpenetrates the collagenous network as well as the external part of the demineralized dentin tubule walls. The amphiphilic character it bears makes it possible to bond to the hydrophilic dentin surface as well as the hydrophobic sealer (bonding agent) or resin composite. The sealer or bonding agent will bond to the hydrophobic part of the primer and the hybrid layer will be created that consists of a collagen network embedded in adhesive resin. Dentin tubules will then be sealed leading to the prevention of leakage of bacteria or toxins, as the resin composite and the tooth tissues are bonded.

The modern systems of enamel-dentin bonding can be divided into different categories that include:

- Three-step or two-step etch and rinse systems. The primer and sealer are combined in the two-step systems.
- Two- or one-step self-etching systems. The acidic primers are not rinsed off in these systems.

Using self-etching bonding system has some advantages including simplicity, low technique sensitivity, and less operative time is required. However, in one study, results have showed that three- and two-step etch and rinse systems are more reliable than the self-etching systems.[95] Although there was improvement on bonding to dentin, the dentin bonding was generally accepted among dentists in the mid 1990s. Most dental schools in the United States (US) claimed that total-etching was quite harmful to the pulp, but this claim was dismissed by Kanca.[96,97] Gwinnett and Kanca further showed that

improvement of bonding to dentin could be possible during the bonding procedure if the dentin surface was kept moist.[98] Nowadays the total-etch and dentin bonding has been a generally accepted concept.[99-103]

Polymerization Shrinkage

The shrinkage of composite resins during polymerization is well documented and shrinkage brings about various challenges during light curing as well as during placement. In some instances, the transfer of shrinkage stresses may bring about coronal deformation, which consequently brings about postoperative sensitivity as well as the propagation of the already present enamel microcracks. The size of these stresses is dependent on several factors such as rate of polymerization and restorative techniques, resin modulus of elasticity, and C-factor (cavity configuration). C-factor is determined by getting the ratio between bonded and unbonded surfaces, a higher ratio signifies higher polymerization stress.

Internal Adaptation and Adhesion to Tooth Structure

Resin composite adaptation is one of the most important contributing factors that may affect the long-term performance of RBCs including their esthetics and longevity.[3] Brunthaler et al. reviewed many prospective clinical studies of direct posterior composite restorations and reported that one of the reasons for restoration failure was post-operative pain or sensitivity. The percent of failures due to post-operative pain or sensitivity ranged from 2 percent to 8 percent. Many theories have been proposed for post-operative pain and sensitivity following placement of resin composite restorations. The current theory of dentinal sensitivity is that, within dentinal tubules, any changes in fluid pressure and fluid

movement stimulate pain receptors in the pulp.[2] There are no pain receptors in the dentin and, thus every dentin stimulus that elicits pain must be stimulating the pain receptors in the pulp. Therefore, any resin composite restoration that is not well adapted to the internal cavity surface will end up with internal gaps. The existing gaps between the material and tooth structure will allow fluid collection, which can transmit hydraulic pressure changes during mastication or temperature change into the dentinal tubules. The pain receptors in the pulp will be stimulated by the changes in hydraulic pressure within the dentinal tubules and the patient will feel pain accordingly. Thus, it is necessary for the resin composite restoration material to be well adapted to the internal cavity surfaces.

Effect of the Placement Technique on Internal Adaptation

The bulk fill RBCs boast of the particularity of having the option to be placed in 4-mm thick bulk without having negative effects on the polymerization shrinkage or the degree of conversion (DC). It has been stated by manufacturers that these materials have polymerization shrinkage that is relatively lower than that of conventional RBCs.[104] Consequently, polymerization shrinkage related problems such as post-operative sensitivity when chewing, gap formation causing secondary caries as a result of bacterial colonization, cusp deflection resulting from high C factor, or pulp irritation could be minimized.[5,78,105-107]

The bulk fill material which is known as Surefil® SDR™ (Smart Dentin Replacement, shrinkage decreased resin) flow has the characteristic of lowering the polymerization shrinkage. This is due to its polymerization modulator, which has been embedded chemically within the central part of the polymerizable resin backbone of the SDR™ monomer.[23]

Studies carried out on RBCs with SDR™ technology indicated significantly lower values of shrinkage stress when compared with others, which included regular flowable RBCs, nano- and hybrid RBCs and other silorane-based composites.[81,90,108]

Packables were introduced in 1990 to provide materials that could address the challenges faced by incremental placement. The packables had a relatively higher viscosity and also contained higher filler loads. Many packables can be bulk placed, that is, they can be placed and cured in 4-mm to 5-mm incremental. One of the challenges faced by the packables in internal adaptation is the high viscosity, which makes it more challenging to adapt to the cavity surface. The actual depth of cure of the packables has been confirmed to be less than claimed. Furthermore, the clinical repercussions of shrinkage stress are more prominent with thicker layers of 4 mm to 5 mm. Most of these materials have been shown by studies to have high shrinkage as well as polymerization stress. A 3M ESPE test method known as cusp deflection was designed to bring about a relative estimate of polymerization shrinkage stress, which originated from placing and curing a dental composite in an open-ended cavity of 4 mm by 4 mm.

Studies have also shown that flowable restoratives have been used to minimize most of the challenges posed by the placement of higher viscosity posterior universal composites. The composites have the ability to flow better than conventional composites. This makes adaptation relatively easier with minimal manipulation of the material. A majority of dentists who use flowables apply them as liners in posterior restorations in order to exploit their ease of adaptation on the cavity surface. However, flowables have relatively lower physical as well as wear resistance properties, which limit their application as filling materials for restorations. It has been shown by researchers that

flowables have higher polymerization shrinkage as compared to most conventional composites. However, it is believed by dentists that a lower modulus has the ability to help in the formation of a stress reducing layer and also to improve marginal integrity although no research has supported this theory.[109] On the other hand, it has been shown by some studies that the flowables may minimize the effects of cusp deflection and consequently reduce gap formation which can bring about post-operative sensitivity.[109]

MATERIALS AND METHODS

TOOTH PREPARATION

Seventy extracted, unrestored, and caries-free human maxillary (n = 13) and mandibular (n = 57) molar teeth were collected and stored in 0.10-percent thymol (Indiana University/ IRB number; 1505861672) until they were used in this *in-vitro* study. The teeth were cleaned with a dental scaler, polished with a rubber cup and flour of pumice (Miltex Pumice flour, Integra® Miltex®, USA) and stored in distilled water (grade 3, ISO 3696) in a refrigerator, i.e., nominal 4^{o}C until use. Part of the occlusal surface of each tooth was removed by grinding it at a right angle to the long axis of the tooth using a 400- grit silicon carbide paper under water lubrication leaving the enamel intact at the center of the tooth. This resulted in creation of a flat exposed dentin surface at the cusp tip areas with enamel located at the center, which allowed the entire cavity occlusal cavosurface margin to be in enamel. This step was required to allow the light curing units to be held at a repeatable distance from the occlusal margin when photocuring each tooth. In addition, the root portion was removed up to 1 mm apical to the cementoenamel junction parallel to the occlusal flat surface to simplify the later sectioning procedure for each specimen by using an ISOMET 1000 precision saw (Buehler, Lake Bluff, IL) under water cooling. The teeth were stored in artificial saliva that had a pH equals to 7 at 37 ^{o}C with the composition listed in Table II.

In the central fossa of each tooth, a Class I cavity (C-factor = 5.0) was prepared with a straight fissure carbide bur with a rounded end (cylindrical) #1158 (SS White Bur Inc., part #17709) at high-speed in a contra angle air-turbine handpiece with air/water

spray. The teeth together with the handpiece were mounted on a Lathe Model 4100 (Sherline Products Inc., Vista, CA) to produce repeated cavity preparation dimensions (Figure 1). The teeth were mounted on the stationary part while the handpiece was mounted using metal screws on the movable part of the lathe machine to assure the stability of the handpiece during cavity preparation (Figure 2). The Lathe movement was linear with measuring wheels that permitted movement in millimeter precision (Figure 3). The cavity dimensions were as following: The buccolingual extension was 2 mm (±0.2 mm); the mesiodistal extension was 6 mm (±0.2 mm), and the occlusogingival depth of each cavity was 4 mm (±0.2 mm). The initial entrance of the bur was made at the mesial pit perpendicular to the long access of each tooth with the depth of 3.5 mm, crossing the central groove (of the lower molars) and the oblique ridge (of the upper molars) whenever necessary to obtain the cavity 6 mm mesiodistal extension. The bur was changed after every five cavity preparations. The internal angles were rounded, and the cavosurface margins were angled approximately 90^{o} (Figure 4). The dimensions of each preparation were measured using a Michigan-O probe (Hu-Friedy Mfg. Co., Chicago, IL) under X3.0 operator loupe magnification with LED headlight illumination (SurgiTel/General Scientific Corp.) and any required slight cavity modification was made manually to ensure all the cavities had the same dimensions with the deepest part from the cavosurface margin equal to 4 mm.

All cavities were checked for cracks at the margins, which could have impacted the final results using a Polaroid Digital Microscope Camera. In addition, preparations with observed pulpal exposure were not used in the experiment, because an entirely intact preparation margin was mandatory for analysis.

RESTORATIVE PROCEDURE

The 70 prepared teeth were randomly distributed to five experimental groups and each group contained at least 2 upper molar teeth (n = 14). Each group was restored with a different RBC system.

The experiment materials were selected from bulk-fill resins produced by popular dental manufacturers. The selection of bulk-fill resin composite materials included those that can be placed in a single 4.0-mm increment, and that do not require a conventional high-viscosity composite to be placed/cured on top of the 4.0-mm thick composite base. In contrast, most posterior bulk-fill flowable composite materials require such a layer to enhance their physical properties.

The RBC material systems were: a traditional universal composite placed by multi-increment-fill technique (Filtek Supreme Ultra Universal Restorative; 3M ESPE, St. Paul, MN), Four composite materials placed by a bulk-fill technique (Tetric EvoCeram Bulk Fill; Ivoclar Vivadent, Schaan, Liechtenstein), (SonicFill; Kerr, West Collins, Orange, CA), (QuiXX Posterior Restorative; Dentsply DeTrey GmbH, Konstanz, Germany), and (x-tra fil; Voco GmbH, Cuxhaven, Germany) (Table III).

All the prepared cavities were acid etched and bonded by using the same system (Kerr Gel Etchant and OptiBond Solo Plus; Kerr, West Collins, Orange, CA) to reduce the number of variables as there is no manufacturer restriction for using the adhesive with the previously selected resin composite materials. In this study, a two-step etch and rinse system had been used as it had more reliable results than the self-etching system.[99] Each cavity was etched with 37.5-percent phosphoric acid (Kerr Gel Etchant; Kerr, West Collins, Orange, CA) using a total-etch technique for 15 seconds and then rinsed

thoroughly with copious amounts of water for 15 seconds. A moist dentin surface was maintained by blotting excess moisture from the dentin with a cotton pellet. Then, two layers of light cure single-component, total-etch bonding agent were applied by using a micro brush, using a light brushing rubbing motion for 15 seconds for each layer (OptiBond Solo Plus; Kerr, West Collins, Orange, CA). After applying a weak stream of air for 3 seconds to disperse the bonding agent into a thin layer, it was light cured with visible light (DEMI LED light curing system, Kerr) and irradiance of 1615 mW/cm^2 for 20 seconds. Light output was monitored using a Managing Accurate Resin Curing calibrator (MARC Resin Calibrator; BlueLight Analytics Inc., Canada). The light-curing tip was placed perpendicular to the cavosurface margin of the cavity. The light tip was fixed at 3.0-mm distance from cavosurface margin to achieve maximum curing depth and to maintain this fixed distance. The curing light tip was fixed using the benchMARC™ adjustable arm clamp that is attached to a bench plate (MARC Resin Calibrator; BlueLight Analytics Inc., Canada) (Figure 5). The distance from the cavity occlusal margin up to the cure light tip was measured by using a Michigan-O probe. All of the restorative materials were packed to the cavity floor and walls by using the same blunt plastic instrument then light cured according to the manufacturer instructions.

FSU Group (Control)

The cavities were restored with traditional universal composite material (Filtek Supreme Ultra Universal Restorative) using an oblique incremental layering technique with five wedge-shaped composite increments from the pulpal floor to the occlusal surface (each increment being not more than 2-mm thick). The first increment of material was placed against the mesial wall and the pulpal floor and then polymerized. Material

was then placed against the distal wall to the pulpal floor and polymerized. This procedure was repeated to place the third increment against the mesial wall, and the fourth one against the distal wall. No increment was placed at any time that would contact both the mesial and distal walls of the preparation. The last increment filled the remaining part up to the occlusal portion of the preparation (Figure 6). Each layer or increment was cured for 20 seconds according to manufacturer instructions (Table IV) from the occlusal surface with a visible light-curing unit (DEMI LED light curing system, Kerr) and irradiance of 1615 mW/cm^2. The curing process was initiated by using a light tip that was perpendicular to the restoration occlusal surface and fixed within a 3.0-mm distance from it using the same previously described method.

TEC Group

The cavities were restored with Tetric EvoCeram Bulk Fill composite-based material using a bulk-fill placement technique. It was placed in a 4.0-mm bulk increment, then light-cured for 10 seconds by the previously described method for FSU group.

SF Group

The cavities were restored with SonicFill composite-based material. This material was activated by a SonicFill handpiece (sonically activated delivery) that converted it to a low viscosity during placement. It was placed in a 4.0-mm bulk increment, and then light cured for 20 seconds by the previously described method for FSU group. Additional cure from the facial and lingual surfaces was performed following the manufacturer recommendation.

QX Group

The cavities were restored with QuiXX Posterior Restorative composite-based material using a bulk-fill placement technique. It was placed in a 4.0-mm bulk increment, and then light cured for 10 seconds by the previously described method for FSU group. Additional cure from the facial and lingual surfaces was performed following the manufacturer recommendation.

XF Group

The cavities were restored with x-tra fil composite-based material using a bulk-fill placement technique. It was placed in a 4.0-mm bulk increment, and then light cured for 10 seconds by the previously described method for FSU group. Additional cure from the facial and lingual surfaces was performed following the manufacturer recommendation (Figure 7).

SPECIMEN PRERARATION AND AGING METHODS

Each group of samples was divided equally into two groups with seven teeth each. The first group was the control group, and the second group was the aged group. The control group specimens were immersed in artificial saliva at 37^{o}C and dark-stored for at least 48 hours until their next use to ensure complete material polymerization. In the aged group, all specimens were immersed in artificial saliva at 37^{o}C for 48 hours and then thermocycled (SD Mechatronik Thermocycler, SD Mechatronik GmbH, Germany) (Figure 8) for 5000 cycles between 5^{o}C and 55^{o}C, with a dwell time of 30 seconds and a transfer time of 10 seconds that corresponded to six months of *in-vivo* functioning to mimic long-term bonding effectiveness (Figure 9).[110]

TEETH SECTIONING AND LABELING PROCEDURES

After the aging procedure, each tooth from both groups was sectioned occlusogingivally perpendicular to the cavity occlusal surface from the most mesial margin to the most distal margin of the restoration with four cuts, in order to create three 2.0-mm thick slices for each tooth with an ISOMET 1000 precision saw (Buehler, Lake Bluff, IL) under water-cooling (Figure 10). This procedure created a flat surface on both sides of each slice that simplified mounting, finishing, and polishing procedures, thus permitting more accurate results. Later research measurements were conducted on the exposed filling material bonded to the tooth structures on one side of the mesial and distal slice, which was the inner one. However, they were conducted on both sides of the middle slice. The specimen sides were labeled: (a) for the inner side of the mesial slice, (b) for the mesial side of the middle slice, (b') for the distal side of the middle slice, and (c) for the inner side of the distal slice (Figure 11, Figure 12).

FINISHING AND POLISHING PROCEDURE

All control group and aged group specimens were mounted on mounting blocks (Struers Inc., Cleveland, OH) and fixed by using sticky wax leaving the resin material side on the top exposed (Figure 13). The exposed surfaces were ground flat and polished (MD-Fuga, Struers Inc., Cleveland, OH) with water-cooled abrasive discs in a circular motion (500- then 1200-grit Al_2O_3 paper with 5 N force for 8 seconds, and 2400- then 4000-grit Al_2O_3 papers with 5 N force for 14 seconds) (Figure 14). Then, they were rinsed with running distilled water for 3 minutes and cleaned for 3 minutes in an ultrasonic bath to remove loose particles and debris (L&R Ultrasonics, L&R

Manufacturing Company, NJ) (Figure 15), and afterward air dried gently. They were polished using a polishing cloth (10 N force for 3 minutes) with a diamond suspension (1 μm DP-Suspension P; Struers Inc.). After polishing procedures, all specimens were immersed in distilled water for 3 minutes, sonicated in detergent for 3 minutes, and then rinsed with running distilled water for 3 minutes (Figure 16). The previously described procedures were repeated for all the teeth middle slices after flipping them. Then, specimens were stored under humid conditions in dark, closed, and labeled containers at 37^{o}C until their next use.

IMAGE RECORDING PROCEDURE

In this study, the internal adaptation, defined as the lack of any space/gap between the tooth structure and the restorative material, was evaluated along the cavity pulpal floor since it was more challenging for the material to adapt to the deepest cavity area compared with the other interface locations. A study done by Furness and associates showed less gap-free margin at the pulpal interface when compared with enamel or mid-dentin interfaces after restoring Class I cavities with different types of bulk-fill RBC materials.[111] The internal adaptation analysis measurements were obtained from a designated area that was 1000-μm long and located at the center of the cavity pulpal floor (Figure 17).

Each individual specimen experimental side (n = 210) was retrieved from its humid storage, and the surface was gently dried immediately before it's use, first by using laboratory delicate task wipes (Kimwipes, Kimtech Science, Kimberly-Clark Global Sales Inc., Roswell, GA), and then by light spray with a compressed-gas duster (Dust Destroyer, Falcon Safety Products Inc., Branchburg, NJ). Afterwards, each

specimen was placed in a light reflection microscope (Instron-Wilson-Tukon Model 2100B) (Figure 18) and multiple digital images were taken and saved for each of a-, b-, b'-, and c-labeled specimen experimental sides (n = 280) by using its simple 1.3 MP high-resolution monochrome CCD digital camera.

The images were obtained and saved using Clemex CMT HD software version 6.0.011 at the cavity pulpal floor and restorative material interface using X200 magnification. Next, X500 magnification was used to confirm any adaptation failure by the existence of gap between the dentin and the restorative material. The images were stitched together by using Adobe Photoshop CS6 to create one panoramic view for each labeled specimen side.

IMAGE ANALYSIS PROCEDURE

The images were quantitatively analyzed by using digital image analysis software (ImageJ, v1.459r, National Institutes of Health, Bethesda, MD, USA). All of the research measurements conducted at a fixed dimensional designated area obtained from each panoramic image named, Region Of Interest (ROI). It was located at the center of each pulpal floor and had dimensions of 1000-μm length and 500-μm height. To eliminate any differences in the pulpal floor length included in the ROI of each specimen due to the variation of pulpal floor curvature that might impact the final results, drawing a line along the inferior border of the pulpal floor using the free hand tool was done. Afterward, the drawn line length was measured and any additional length beyond 1000 μm was cropped from the ROI (Figure 19).

Any presence of gap at the composite/dentin interface was determined and classified into one or more of the following categories based on its location:

i. CA: gap at the composite/adhesive interface

ii. AD: gap at the adhesive/dentin interface

iii. CAD: gap at the composite/adhesive/dentin interface (mixed).

Then each gap boundary was determined and cropped using Adobe Photoshop CS6. Next, each gap area was measured (unit of μm^2) using dimensional calibration based on a high precision stage micrometer after threshold determination using ImageJ (Figure 20). Furthermore, the cavity adaptation (%) was calculated for each specimen with ImageJ utilizing the following equation: cavity adaptation (%) = (sum of adaptation length/ total length of cavity floor)×100. Moreover, any cohesive failure that occurred in the composite-based material or the dentin was documented. In addition, the incidence of any internal void that was surrounded completely by composite-based material was recorded.

The same trained operator prepared and filled all the cavities and completed all the previously described procedures. To insure accuracy, a second trained operator also collected data. The results were consistent.

STATISTICAL ANALYSIS

Summary statistics (n, mean, standard deviation, minimum and maximum) were computed for gap measurement without and with aging of the specimens. This was completed for each of the five restorative material groups and for each of the gap location categories. Mixed-model analysis of variance (ANOVA) was performed to examine the effects of aging, restorative material groups, gap location categories, and specimen slice side with a random effect for the correlation between the slices within each tooth. An additional mixed-model ANOVA was performed to examine the additional effect of gap

location categories, with an additional random effect for correlating the gap location categories within each slice. Fisher's protected LSD test was used to control for multiple comparisons. Due to non-normality in the data regarding the dependent variables were ranked (from smallest to largest) prior to analyses process.

The sum of all gap categories (CA for gap at the composite/adhesive interface, AD for gap at the adhesive/dentin interface, and CAD for gap at the composite/adhesive/dentin interface) and the cavity adaptation values were ranked and then used for the analysis process. There was an additional fixed and random effect in gap measurement analysis in addition to the ranking of the dependent variables of the gap measurement values. A 5.0-percent significance level was used for all comparisons.

With a sample size of 14 teeth per group, the study had 80-percent power to detect a mean gap ratio of 2.5 for one group compared to another, assuming two-sided tests each conducted at a 5.0-percent significance level and assuming the coefficient of variation was 1.

RESULTS

GAP MEASURMENT

Restorative Material Groups

There was a significant difference in gap measurement among different restorative material groups ($p = 0.0333$). The gap measurement for the control group FSU was significantly smaller than SF and XF groups ($p \leq 0.008$). Nevertheless, no significant difference was found between the other restorative material groups (Figure 21).

Gap Location Categories

Regarding the interaction between the gap measurement and different gap categories identified by location (i.e. CA for gap at the composite/adhesive interface, AD for gap at the adhesive/dentin interface, and CAD for gap at the composite/adhesive/dentin interface) there was a significant difference ($p < 0.0001$). The gap measurement for AD was significantly smaller than CA ($p < 0.0001$). But, the gap measurements for AD and CA were significantly larger than CAD ($p \leq 0.0004$) (Figure 22).

Restorative Material Groups and Gap Location Categories

Testing the effect of restorative material group and different gap category on gap measurements indicated a significant interaction ($p < 0.0001$). In the FSU group, the gap measurement for CAD was significantly smaller than CA ($p = 0411$). Gap measurements for AD and CAD were significantly smaller than CA in QX, SF, TEC, XF groups ($p \leq$

0.0024), and for CAD was significantly smaller than AD in QX group (p = 0010) (Figure 23, Figure 24).

Aging Groups

The gap measurement for the aged group was significantly higher than for the control group (p = 0.0452) (Figure 25).

SUM OF ALL GAP CATEGORIES

Restorative Material Groups

Overall, there was a significant difference between the restorative material groups (p = 0.0036). Individual comparisons of the fill groups indicated that the sum of all gap categories in the control group FSU was significantly smaller than the TEC, SF, and XF groups ($p \leq 0.021$), and the sum of all gap categories for QX was significantly smaller than SF (p = 0.0257) (Figure 21).

Slice Sides

The sum of all gap categories for slice side a and side c was significantly larger than b ($p \leq 0.0155$).

Aging Groups

The sum of all gaps for the aged groups was significantly higher than that for the control groups (non-aged) (p = 0.0239) (Figure 25).

CAVITY ADAPTATION (%)

Restorative Material Groups

Generally, there was a significant difference between restorative material groups ($p = 0.0001$). The control group FSU had a higher cavity adaptation than the SF, TEC, and XF groups ($p \leq 0.019$), and the cavity adaptation for the QX and TEC groups were significantly higher than SF group ($p \leq 0.0148$) (Figure 26).

INCIDENCE OF GAP LOCATION CATEGORIES AMONG THE RESTORATIVE MATERIAL GROUPS

The incidence of gap location categories among different restorative material groups shows in (Table V). CA gap category was the highest among all the restorative groups followed by AD gap category. The only two groups that had CAD gap category were QX and TEC.

COHESIVE FAILURE

Any cohesive failure observed in the filling material or the dentin was reported. There were 11 total cohesive failures; 9 failures occurred in the composite, and 2 in the dentin. In particular, 9 failures occurred in the control group, and 2 in the aged group. Most of the failures occurred in XF restorative group with total of 5 failures (Table VI), (Figure 27).

INCIDENCE OF VOIDS IN THE COMPOSITE RESTORATIVE MATERIALS

The incidence of any internal void that was surrounded completely by composite-based material observed in the panoramic view (from the most inferior boarder of the

composite-based material up to 250 μm occlusally) was documented. Overall, there was a significant difference in the probability of a void for the different restorative material groups ($p < 0.0001$). The SF group had a significantly lower probability of voids than FSU, QX, TEC, and XF groups ($p \leq 0.0024$). QX had a significantly lower probability of voids than FSU, TEC, and XF ($p \leq 0.0287$). However, FSU, TEC, and XF did not have significantly different probabilities of voids (Figure 28, Figure 29).

TABLES AND FIGURES

TABLE I

Filler sizes and compositions in dental composite materials

Composite type	Filler size (µm)	Filler material
Macrofilled	10 - 40	Quartz or glass
Microfilled	0.01 – 0.1	Colloidal silica
Hybrid	15 – 20 and 0.01 – 0.05	Glass and colloidal silica
Modern hybrid	0.5 – 1 and 0.01 – 0.05	Glass, zirconia and colloidal silica
Nanofilled	< 0.01 (10 nm)	Silica or zirconia

TABLE II

Artificial saliva (OHRI* recipe with mucin and buffer)

Material	Weight/one liter
$CaCl_2$ *H_2O	0.213g
KH_2PO_4	0.738g
KCl	1.114g
NaCl	0.381g
Tris Buffer	12g
Gastric Mucin	2.20g

*Oral Health Research Institute, Indiana University School of Dentistry, Indianapolis, Indiana.

TABLE III

Materials, manufacturers, and chemical compositions of matrix, filler type, and filler content by weight (wt) and volume (vol)

Group code/product	Manufacture shade, mfg. part #	Resin matrix	Filler composition/ size	Filler amount Wt%/Vol%
Traditional increment-fill resin composite				
FSU: Filtek Supreme Ultra Universal Restorative (nanohybrid)	3M ESPE, A2B, 6029A2B	Bis-GMA, UDMA, TEGDMA, Bis-EMA, PEGDMA	Silica, zirconia, zirconia/silica (0.6 - 10 μm)	78.5/63.3
Bulk-fill resin composites				
TEC: Tetric EvoCeram Bulk Fill (nanohybrid)	Ivoclar Vivadent, universal IVA*, 638244WW	Bis-GMA, UDMA, Bis-EMA	Barium glass, ytterbium trifluoride, mixed oxide, prepolymerized fillers (0.04 - 3 μm)	76 -77/53 - 54
SF: SonicFill (nanohybrid)	Kerr, A2, 34922	Bis-GMA, Bis-EMA TEGDMA, EBPDMA, MPS	SiO2, glass, oxide (0.02 - 40 μm)	67/83.5
QX: QuiXX Posterior Restorative (hybrid)	Dentsply DeTrey GmbH, universal, 631202	UDMA, TEGDMA Di- and trimethacrylate resins, Carboxylic acid modified dimethacrylate resin	Strontium aluminum, Sodium fluoride, Phosphate silicate glass (NP)	86/66
XF: x-tra fil (hybrid)	Voco GmbH, universal, 1741	Bis-GMA, UDMA, TEGDMA	Barium boron aluminum silicate glass (0.05 - 10 μm)	86/70

Abbreviations: Mfg., Manufacturer; Bis-EMA, Bisphenol-A polyethylene glycol diether dimethacrylate; Bis-GMA, Bisphenol-A diglycidyl ether dimethacrylate; EBPDMA, ethoxylated Bisphenol-A-dimethacrylate; TEGDMA, triethylene glycol dimethacrylate; UDMA, urethane dimethacrylate; MPS, 3-trimethoxysilylpropyl methacrylate, PEGDMA; poly(ethylene glycol) dimethacrylates; NP, filler size not provided. *Universal IVA for restorations in the "A" range (A2-A3).

TABLE IV

The manufacturer instructions for use*

Group code	Manufacturer instructions for use
FSU	-Placed in 2.0 mm increment. -Light cure each increment for 20 sec.
TEC	-Placed in one 4.0 mm increment. -Light cure for 10 sec.
SF	-Placed in one 4.0 mm increment. - Light cure for 20 sec. -For Class I, additional cure is recommended from the facial and lingual surfaces.
QX	-Placed in one 4.0 mm increment. - Light cure for 10 sec. -Additional cure is recommended from the facial and lingual surfaces.
XF	-Placed in one 4.0 mm increment. - Light cure for 10 sec. -Additional cure is recommended from the facial and lingual surfaces.

*Information given by the manufacturers.

TABLE V

The incidence of gap location categories among different restorative materials' groups

Gap Location Category / Restorative Material Group	CA	AD	CAD	Total
FSU	7	4	0	11
QX	26	15	3	44
SF	51	5	0	56
TEC	22	6	3	31
XF	27	5	0	32

TABLE VI

Cohesive failure among different restorative material groups

Restorative Material Group	Aging Group	Dentin	Composite	Total
FSU	Control	0	1	3
	Aged	1	1	
QX	Control	0	1	1
	Aged	0	0	
SF	Control	0	0	0
	Aged	0	0	
TEC	Control	0	2	2
	Aged	0	0	
XF	Control	1	4	5
	Aged	0	0	

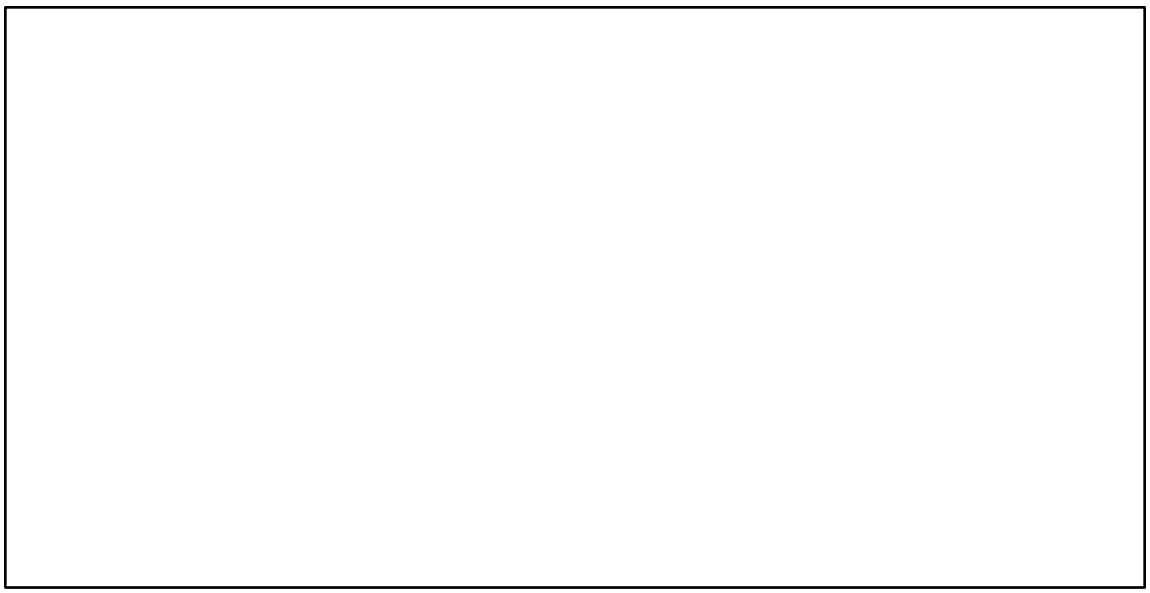

FIGURE 1. Mounted handpiece with metal screws on a Lathe Model 4100 machine.

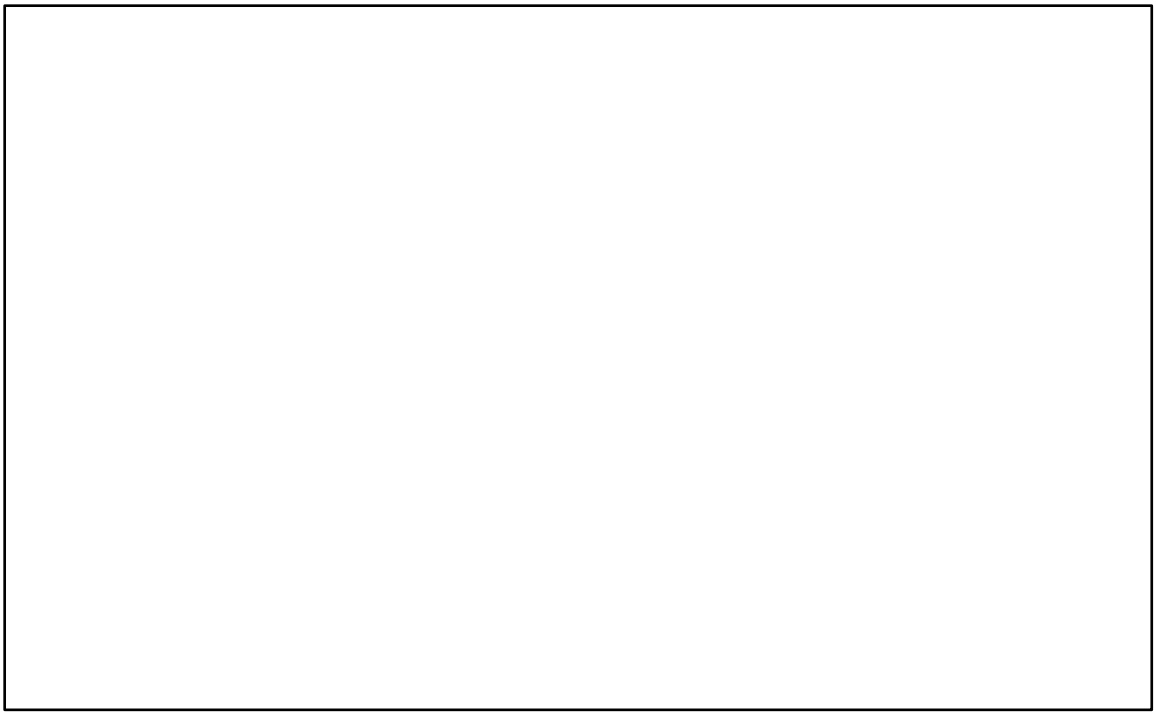

FIGURE 2. The handpiece linear movement towards the tooth with the bur perpendicular on the teeth long access.

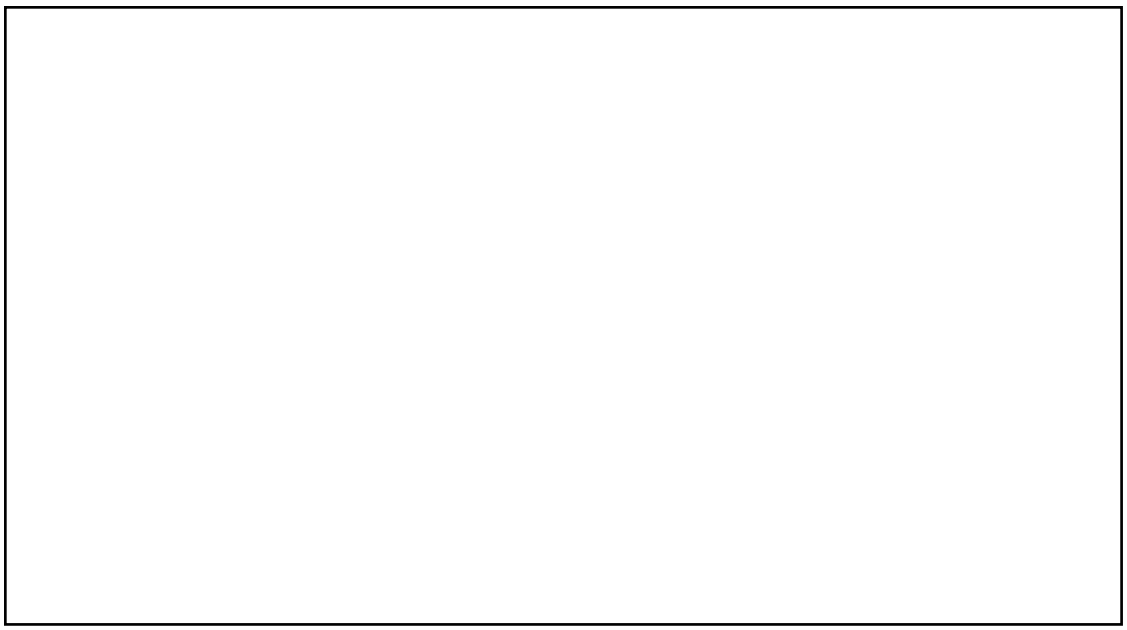

FIGURE 3. The measuring wheels attached to the Lathe machine motional part.

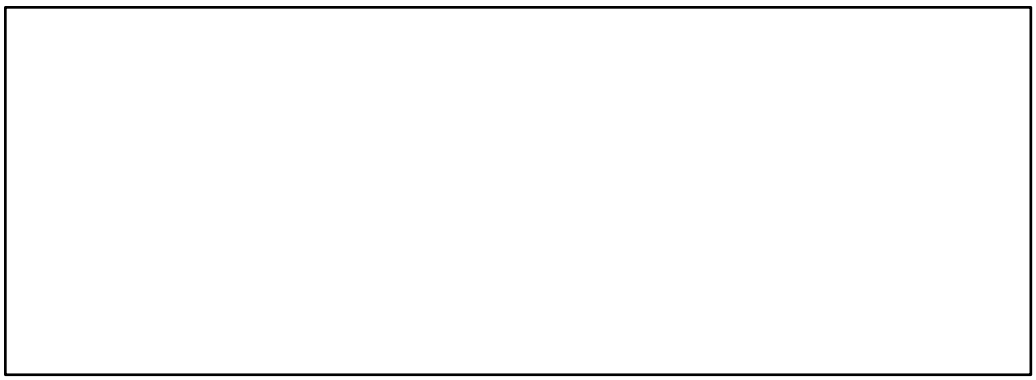

FIGURE 4. A diagram of cusp tips flattening, root sectioning, and cavity preparation.

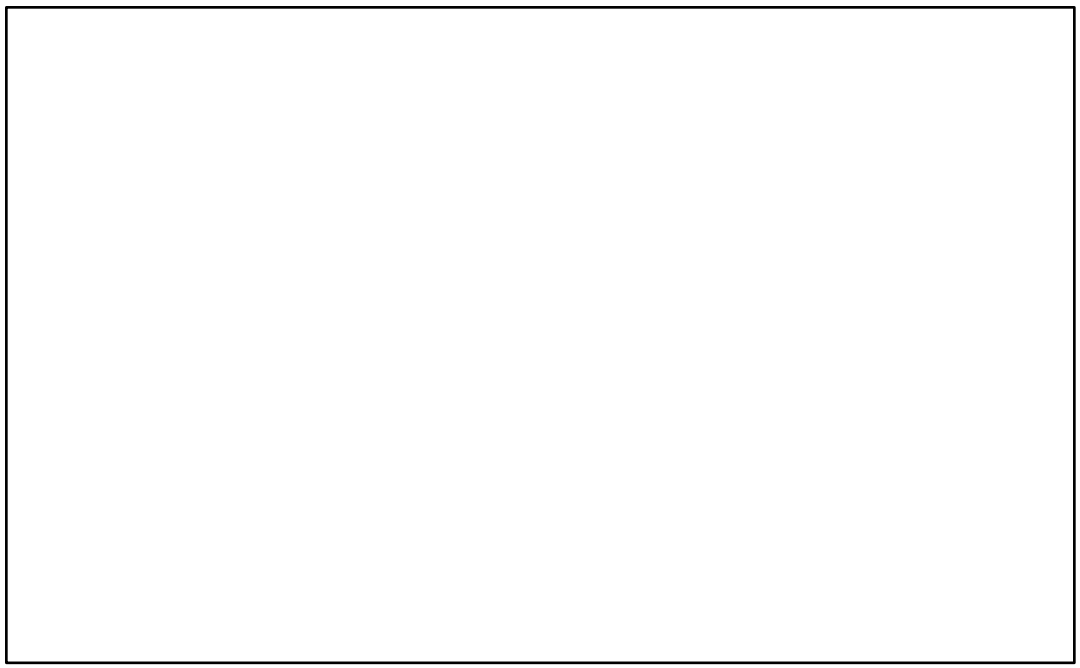

FIGURE 5. MARC Resin Calibrator that was used to maintain a fixed distance during light-curing materials procedure.

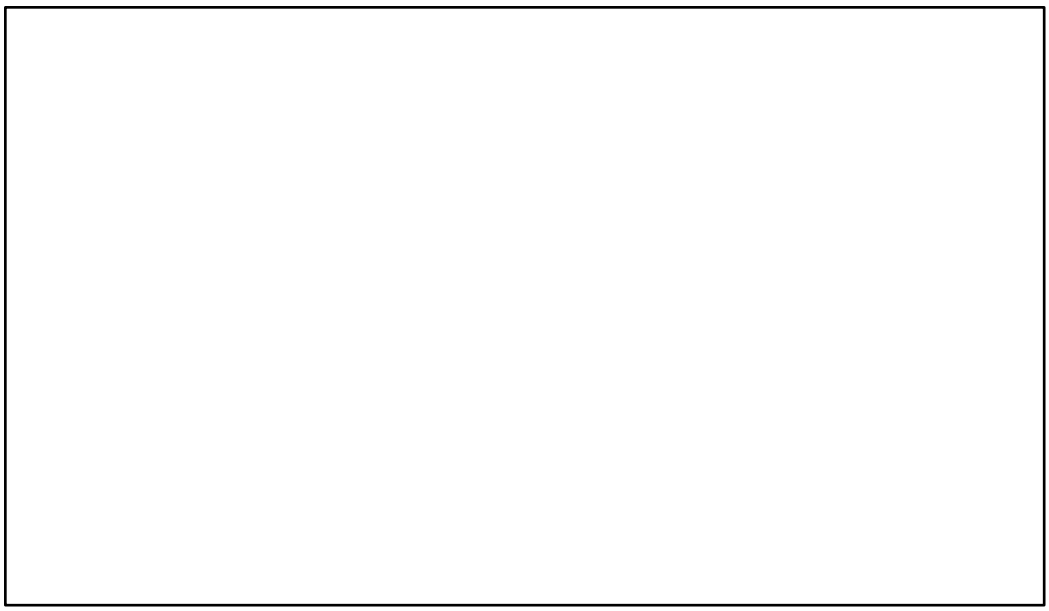

FIGURE 6. Cross-section view shows the incremental buildup of restoration with polymerization following each increment.

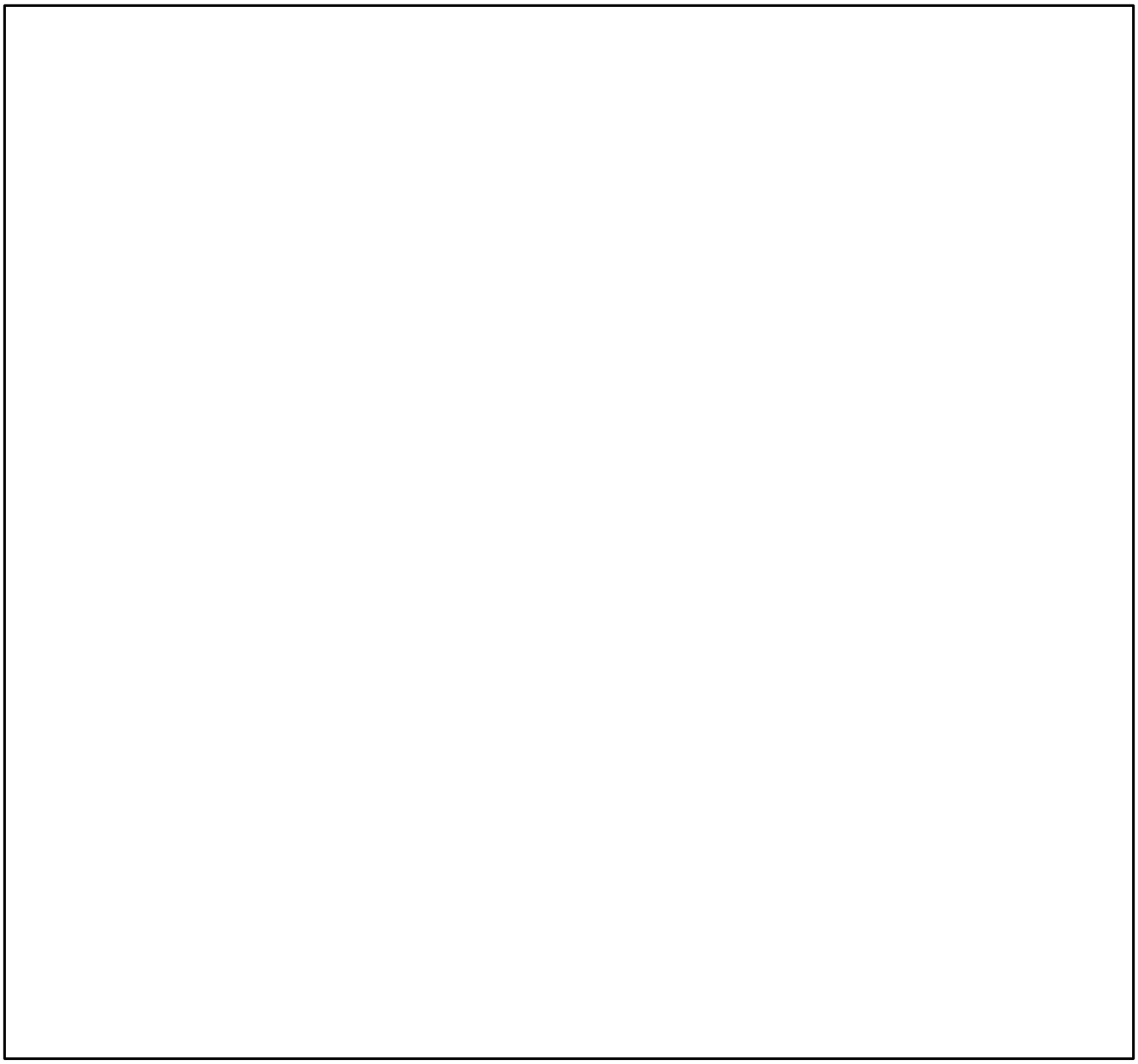

FIGURE 7. Schematic showing the teeth preparation and experimental groups: (a) An occlusal view of the experimental teeth; (b) Cavity preparation dimensions for each tooth, and (c) The five experimental groups, each filled with different resin composite material (14 per group).

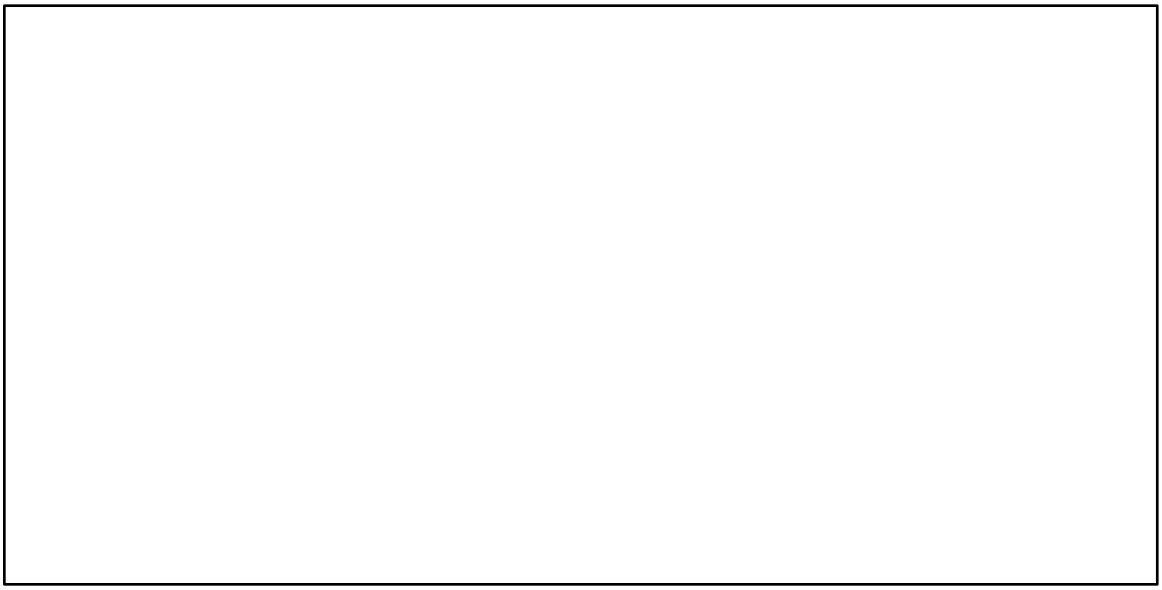

FIGURE 8. SD Mechatronik Thermocycler that was used in aging procedure.

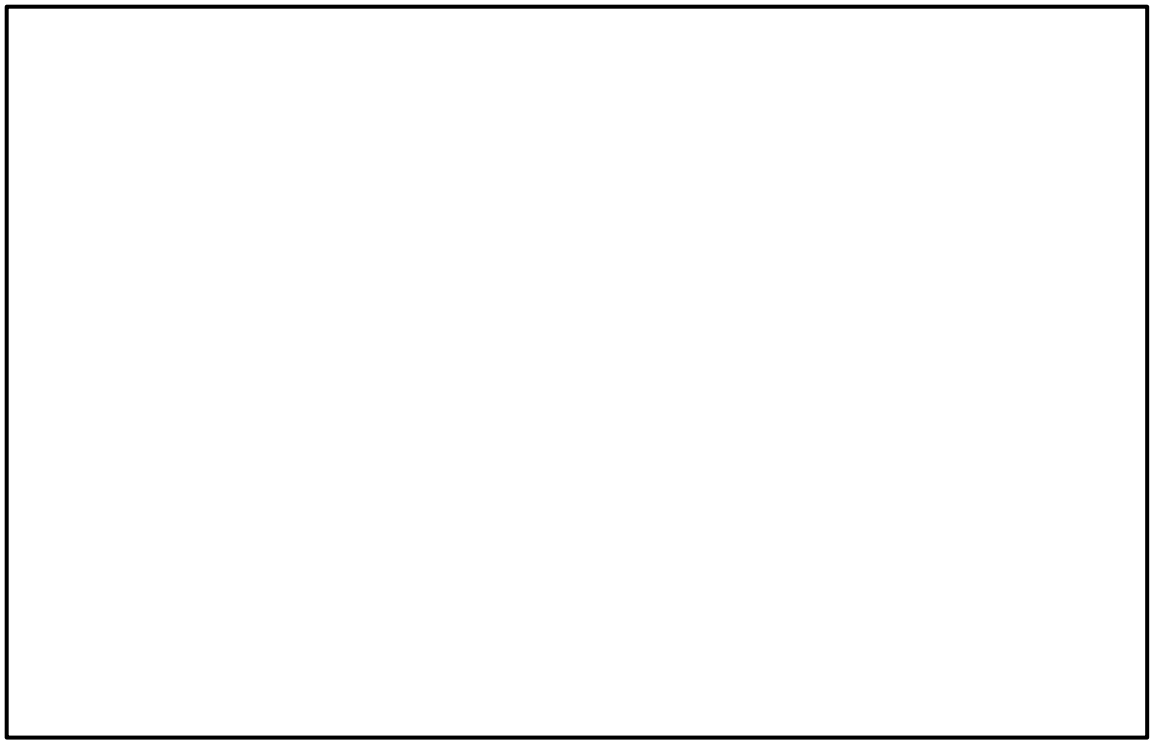

FIGURE 9. A diagram for specimen preparation and aging methods.

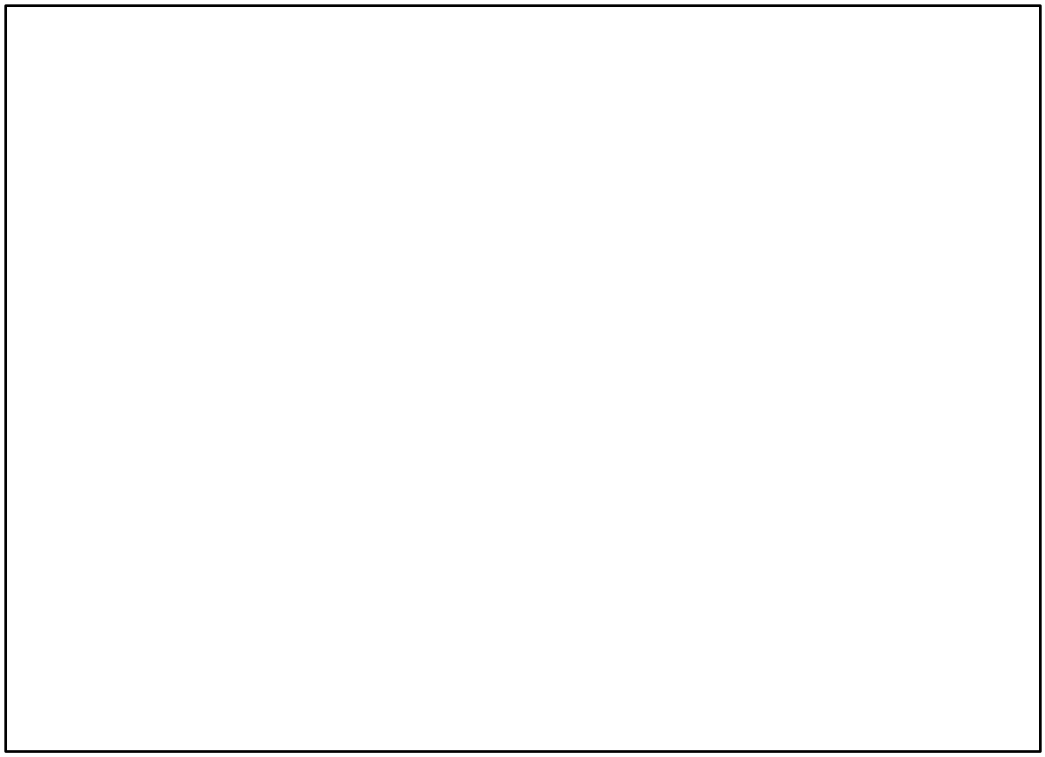

FIGURE 10. ISOMET 1000 precision saw used in specimen sectioning procedure.

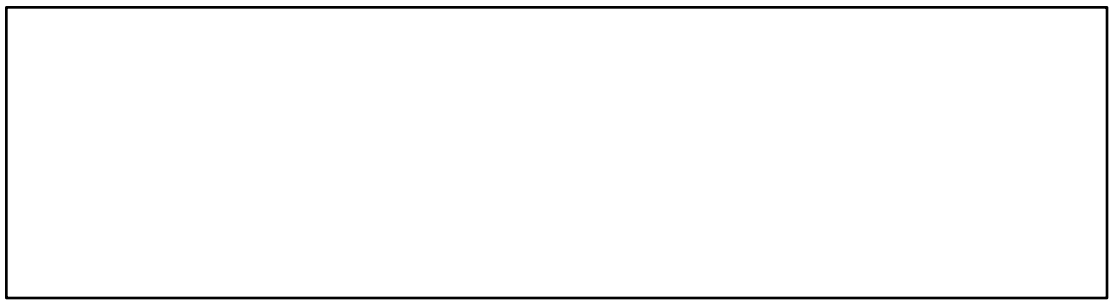

FIGURE 11. Teeth sectioning and labeling procedure. Three slices were created from each tooth and four sides were labeled; a for the inner side of tooth mesial slice, b for the mesial side of tooth middle slice, b’ for the distal side of tooth middle slice, and c for the inner side of tooth distal slice.

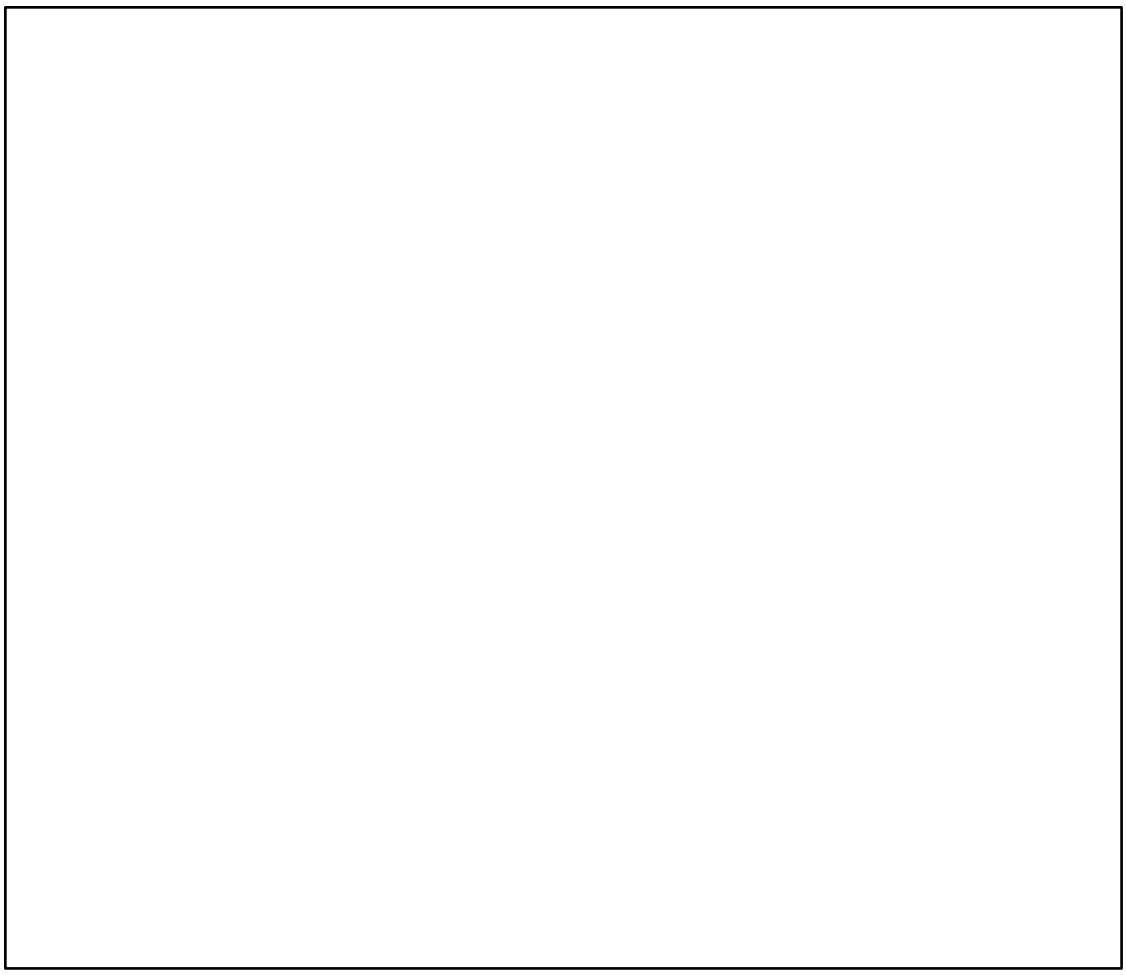

FIGURE 12. An illustration shows tooth preparation steps. (a) Cusp tips flattened and the root portion was removed up to 1mm apical to the cementoenamel junction parallel to the occlusal flat surface, occlusal view shows the flat cusp tips, cavity preparation, and filling placement, (b) Tooth sectioning and three slices were obtained, (c) Labeling the slice sides (a,b,b',c).

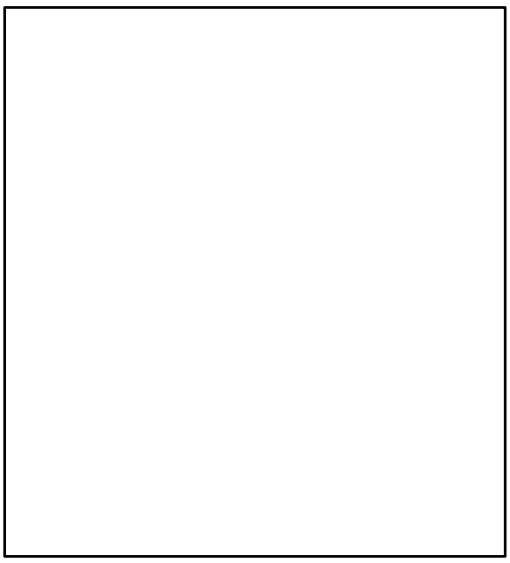

FIGURE 13. Specimens mounting on mounting blocks in preparation to finishing and polishing procedures.

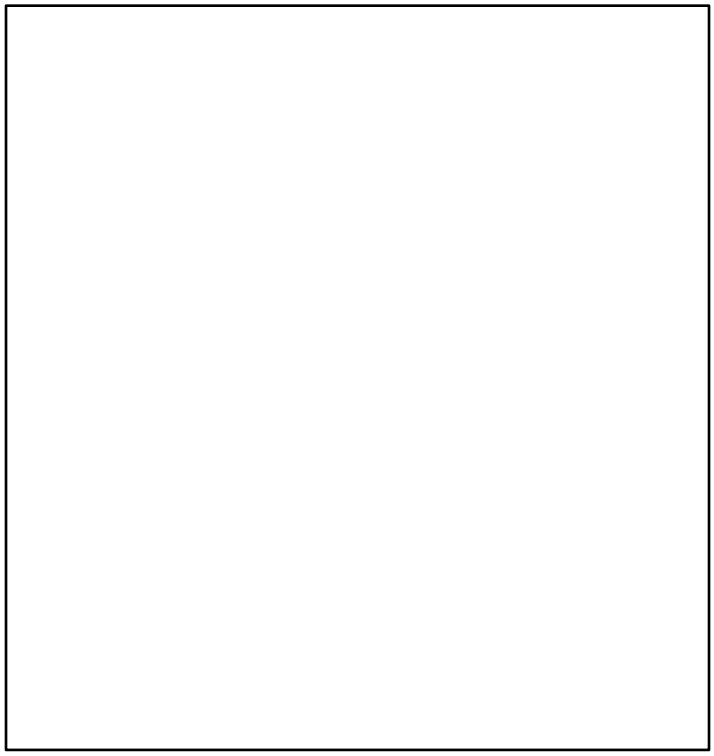

FIGURE 14. MD-Fuga machine that used in specimen finishing and polishing procedures.

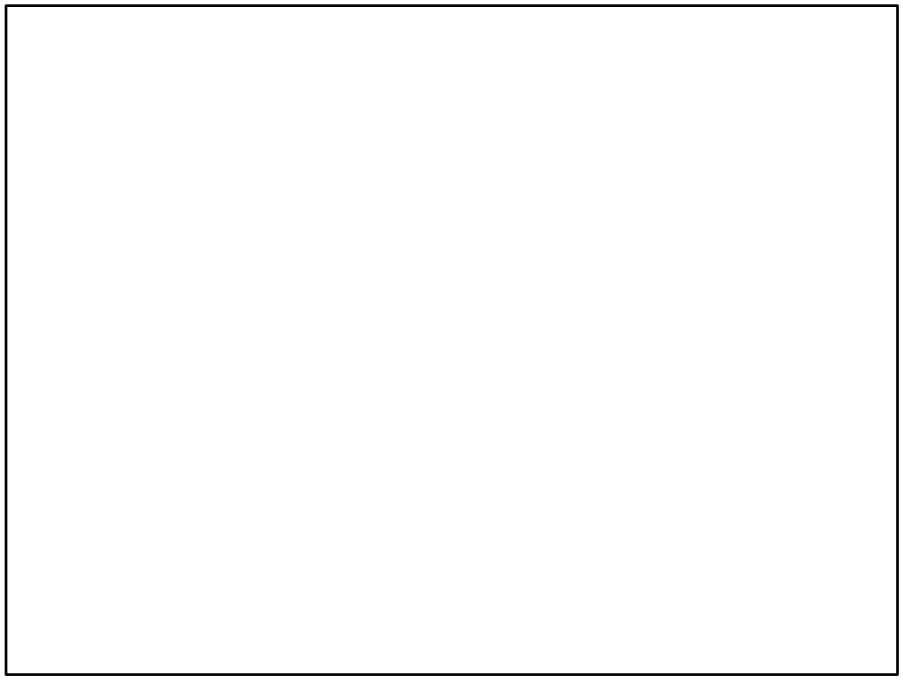

FIGURE 15. Specimens sonication using L&R Ultrasonics to remove finishing and polishing debris.

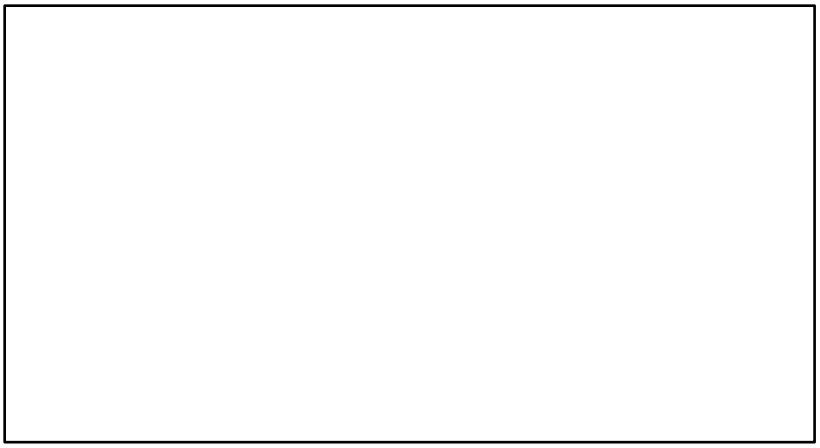

FIGURE 16. Mounted specimens after finishing and polishing procedures.

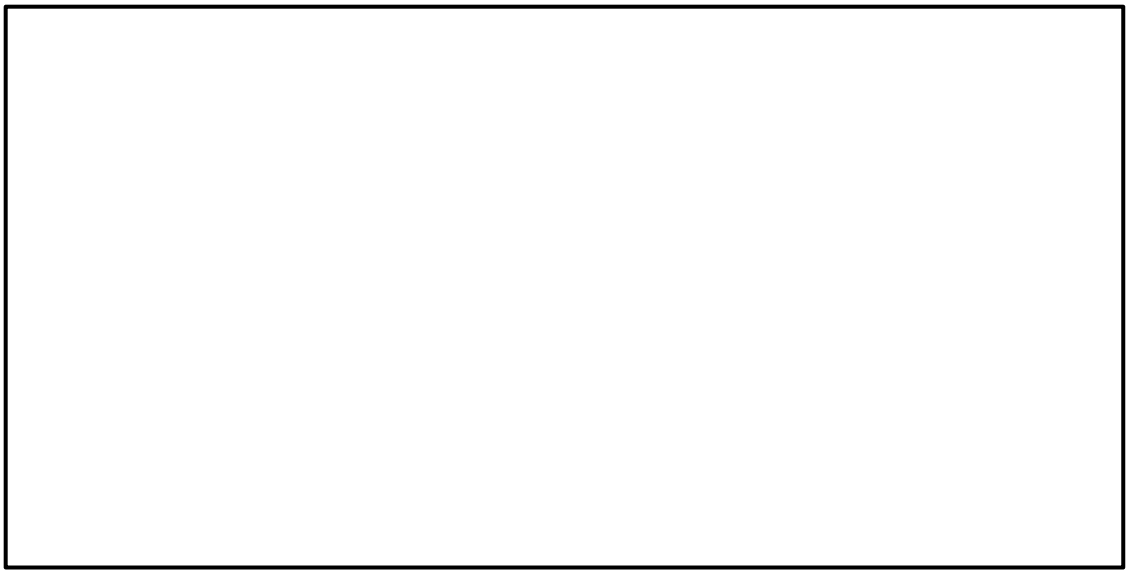

FIGURE 17. The designated area that the study analysis attained was1000 μm long and located at the center of the cavity pulpal floor.

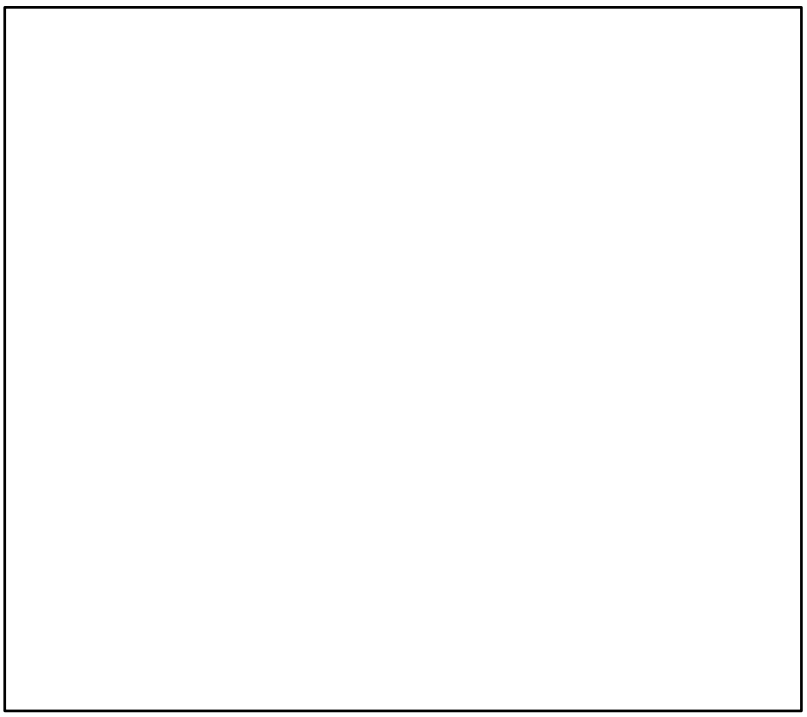

FIGURE 18. Instron-Wilson-Tukon Model 2100B machine used for image recording.

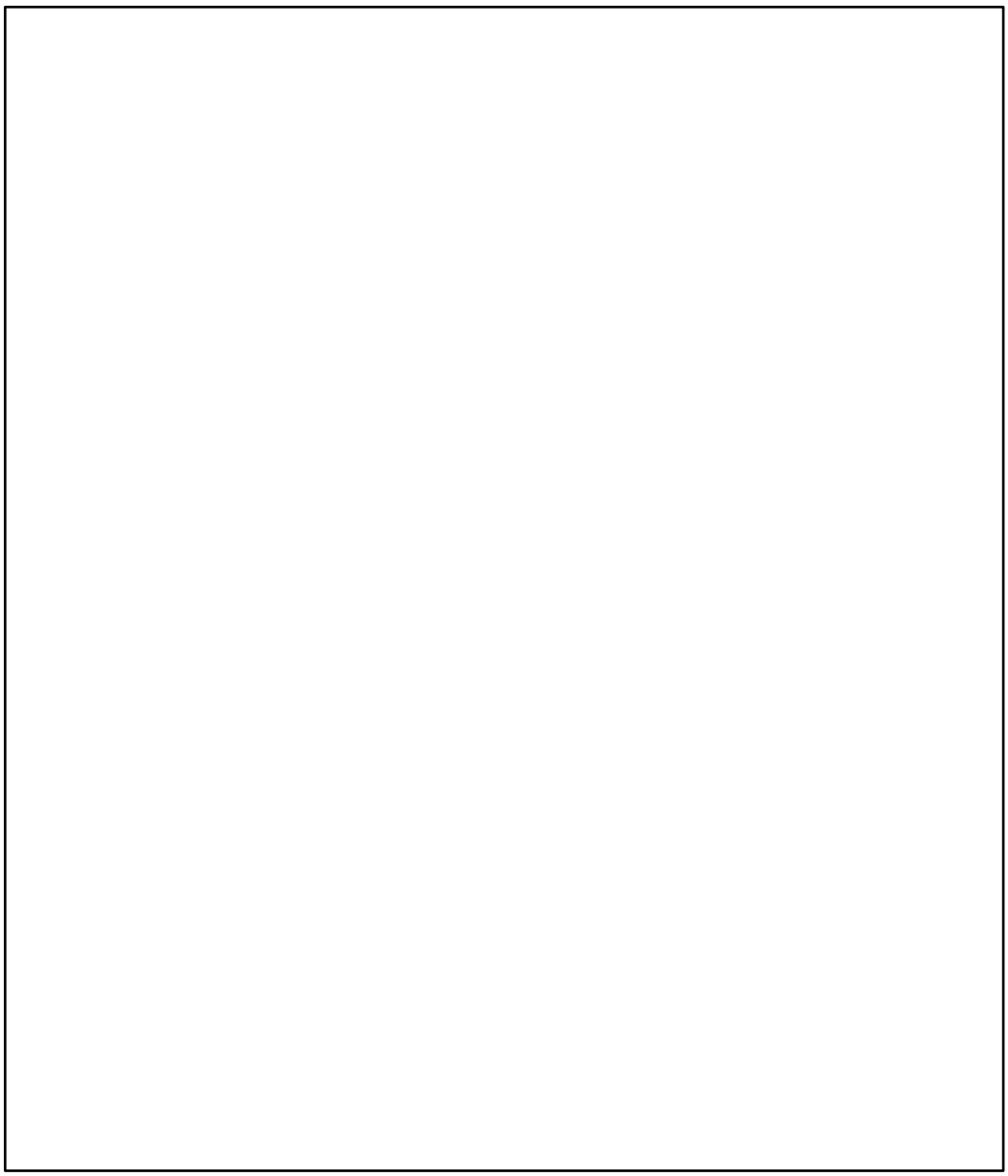

FIGURE 19. Image recording and analysis steps schematic illustration for one of the specimens as an example under X200 magnification. (a) Multiple images collection, (b) Stitching the images together manually to get a panoramic view, (c) Locating Region Of Interest (ROI) window that has specific dimensions, (d) Cropped initial ROI, (e) Measuring the inferior border of pulpal floor length, (f) Adjustment ROI window by excluding any extra pulpal floor length than 1000 μm, (g) Cropping the image and attaining the final ROI.

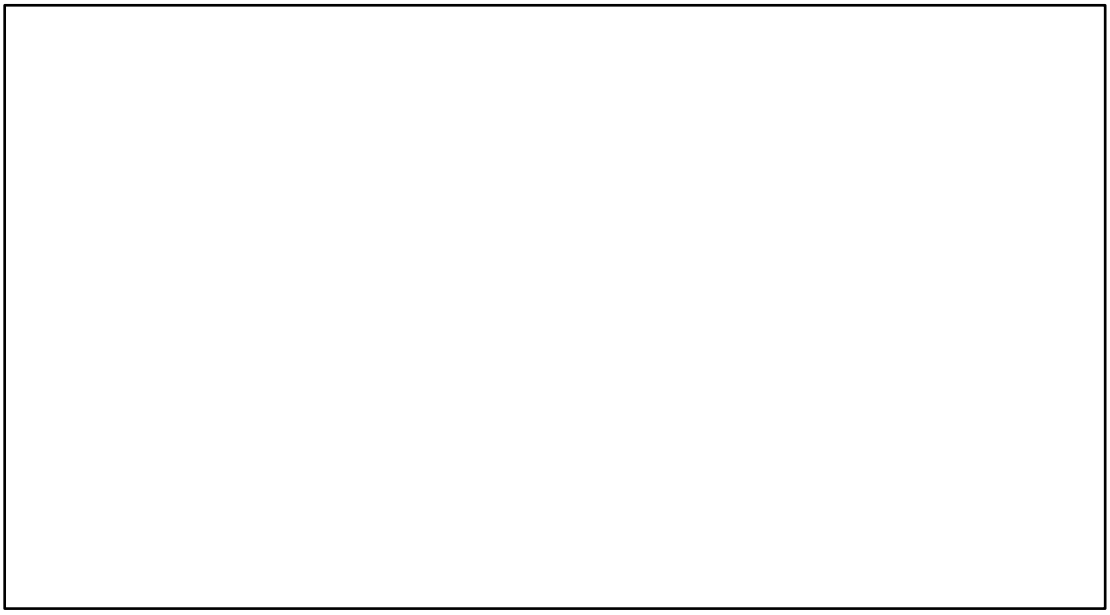

FIGURE 20. Gap determination and analysis steps for one of the specimens as an example under X200 magnification. (a) Determination of the gap margins, (b) Cropped previously determined gap, (c) Threshold the gap and measuring its area.

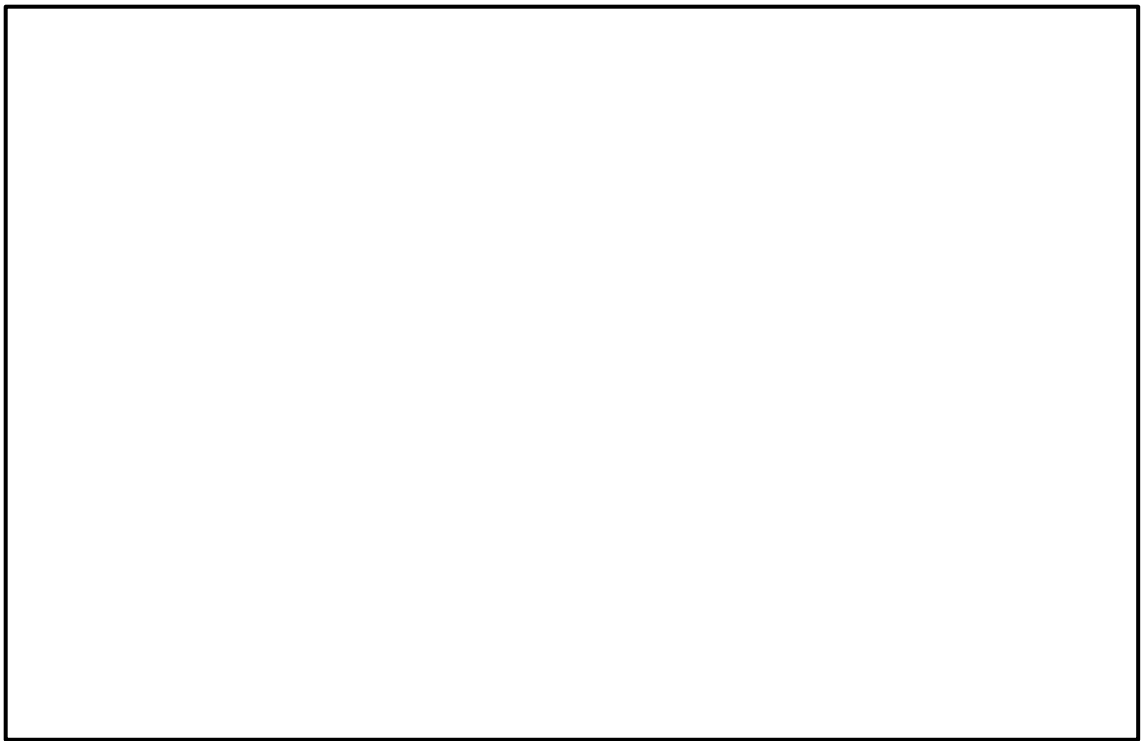

FIGURE 21. Effect of restorative material group on gap measurement. Groups identified with similar letters are not significantly different.

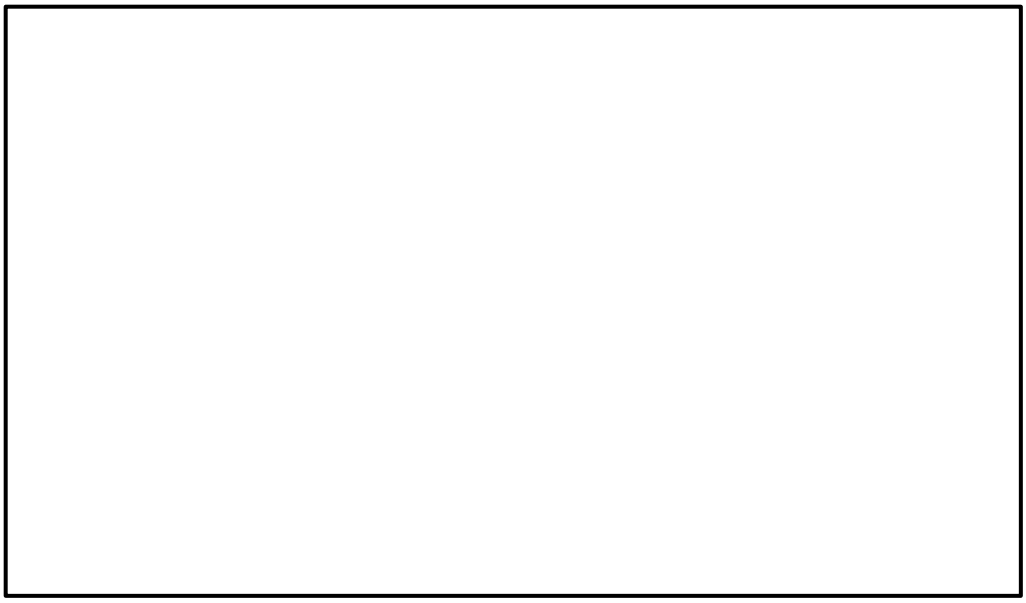

FIGURE 22. Effect of gap location categories on the gap measurement.

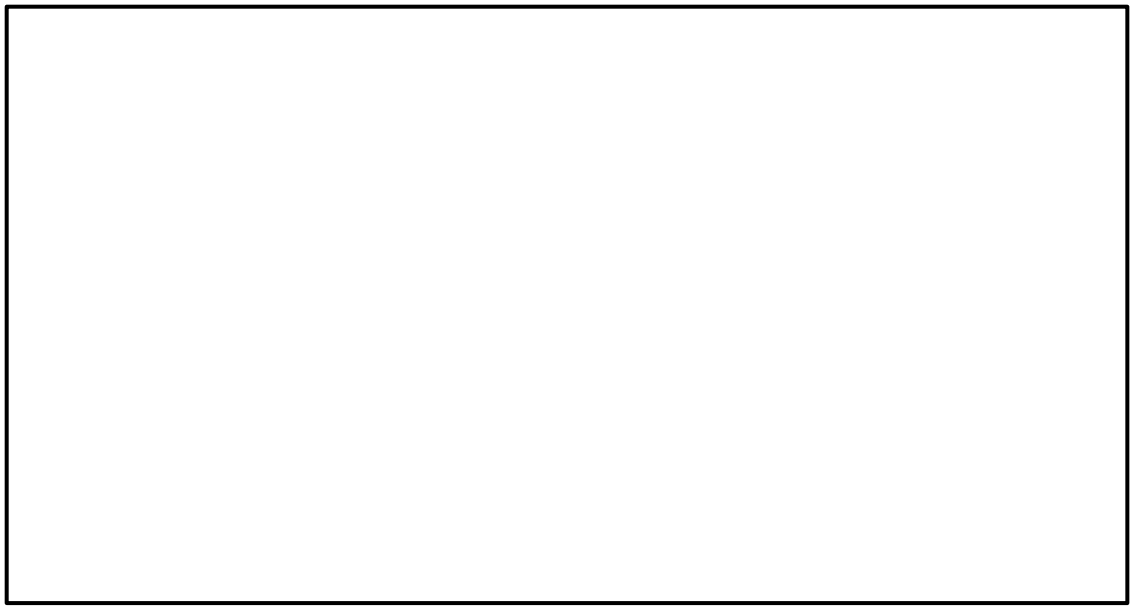

FIGURE 23. Effect of restorative material group and gap location categories on the gap measurement.

FIGURE 24. Panoramic images representing different gap categories. (a) Obtained from FSU group shows no gap at all; (b) Obtained from SF group shows CA gap type; (c) Obtained from XF group shows AD gap type; (d) Obtained from QX group shows CAD gap type.

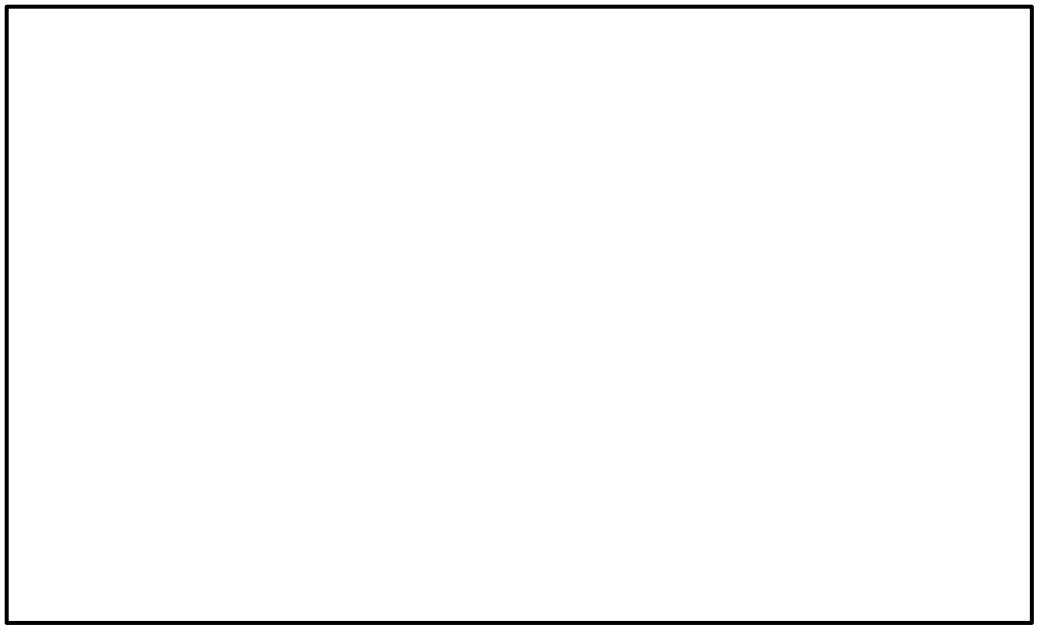

FIGURE 25. Effect of aging group on gap measurement and the sum of all gap categories.

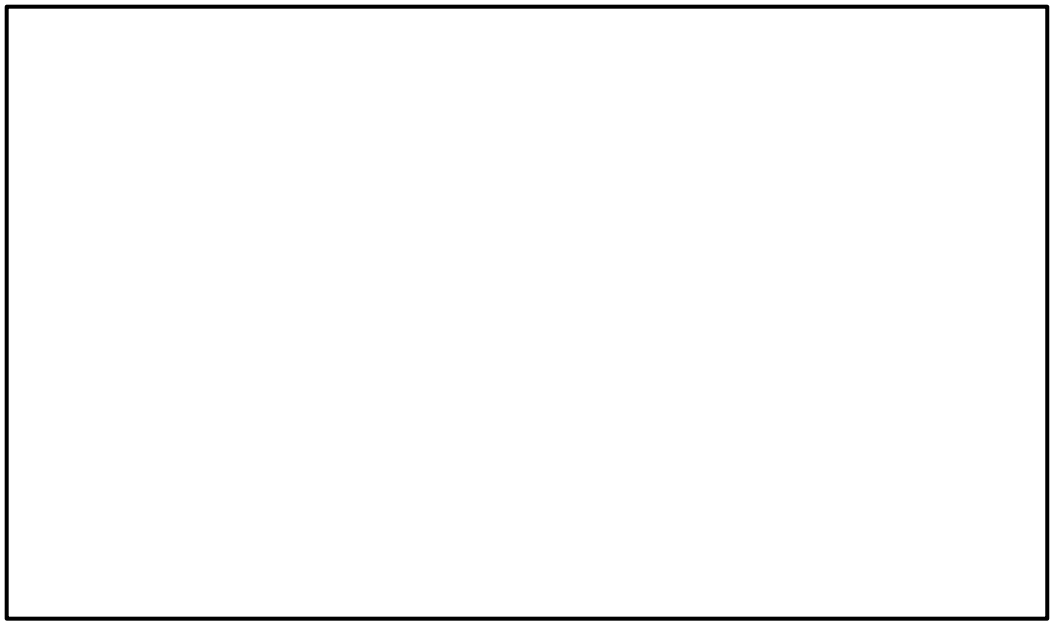

FIGURE 26. Effect of restorative material group on the sum of all gap categories. Groups identified with similar letters are not significantly different.

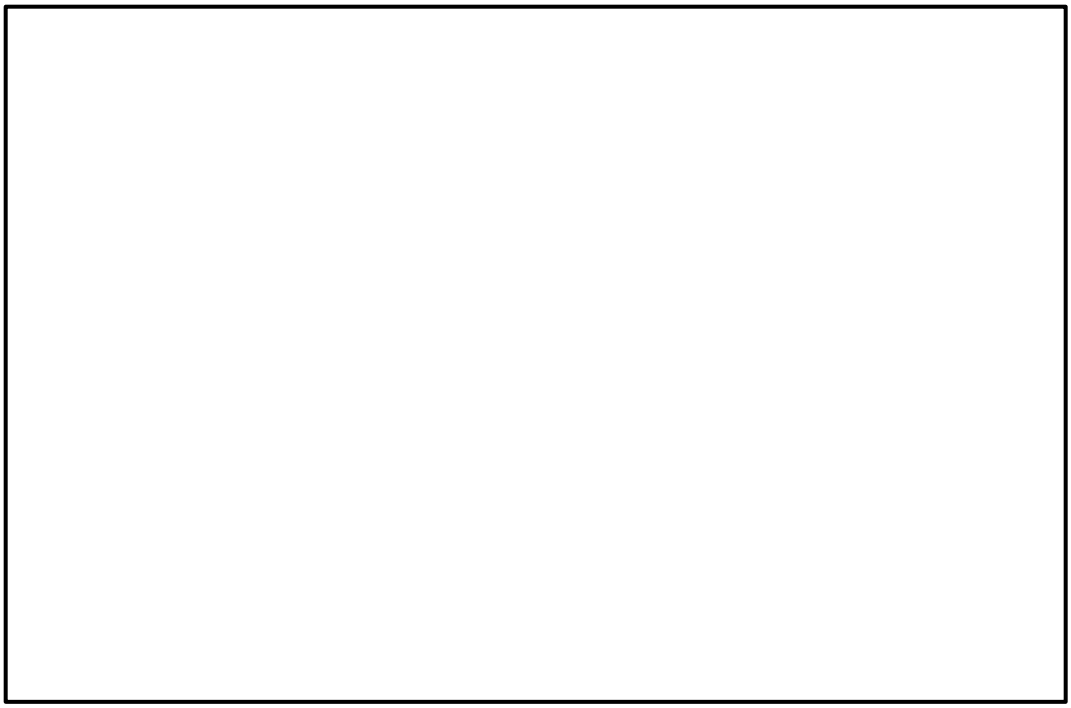

FIGURE 27. Effect of restorative material group on gap measurement and the sum of all gap categories.

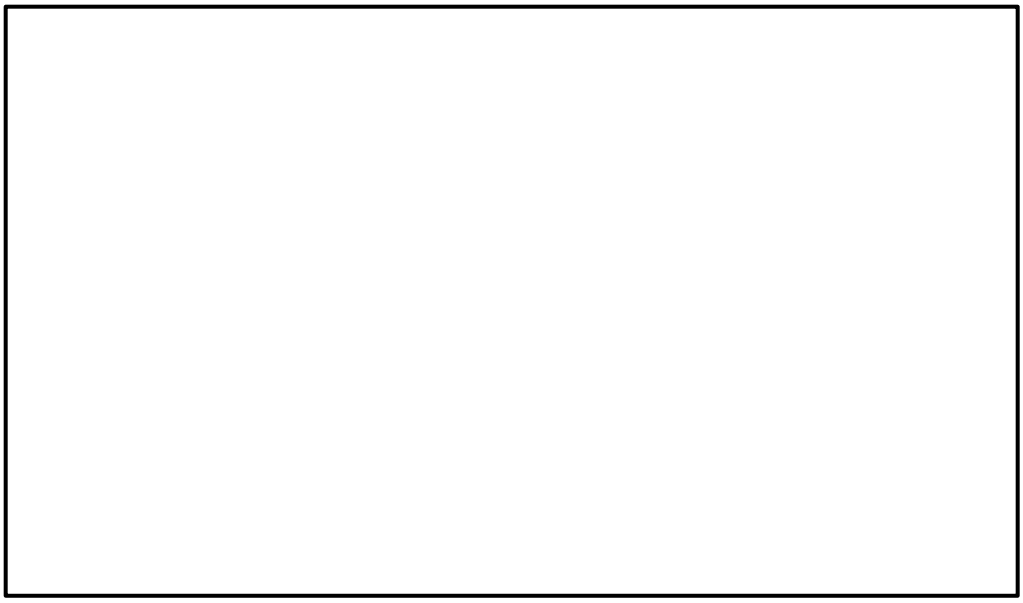

FIGURE 28. Effect of restorative material group on the cavity adaptation (%).

FIGURE 29. Representative images to illustrate cohesive failures. (a) Cohesive failure in RBC with cracked adhesive obtained from one of XF control group samples; (b) cohesive failure in RBC with cracked adhesive obtained from one of TEC control group samples; (c) cohesive failure in RBC with cracked adhesive obtained from one of FSU control group samples. (d), (e), (f) Cohesive failure in RBC with cracked adhesive obtained from different XF control group samples. (g) Cohesive failure in dentine obtained from one of XF control group samples.

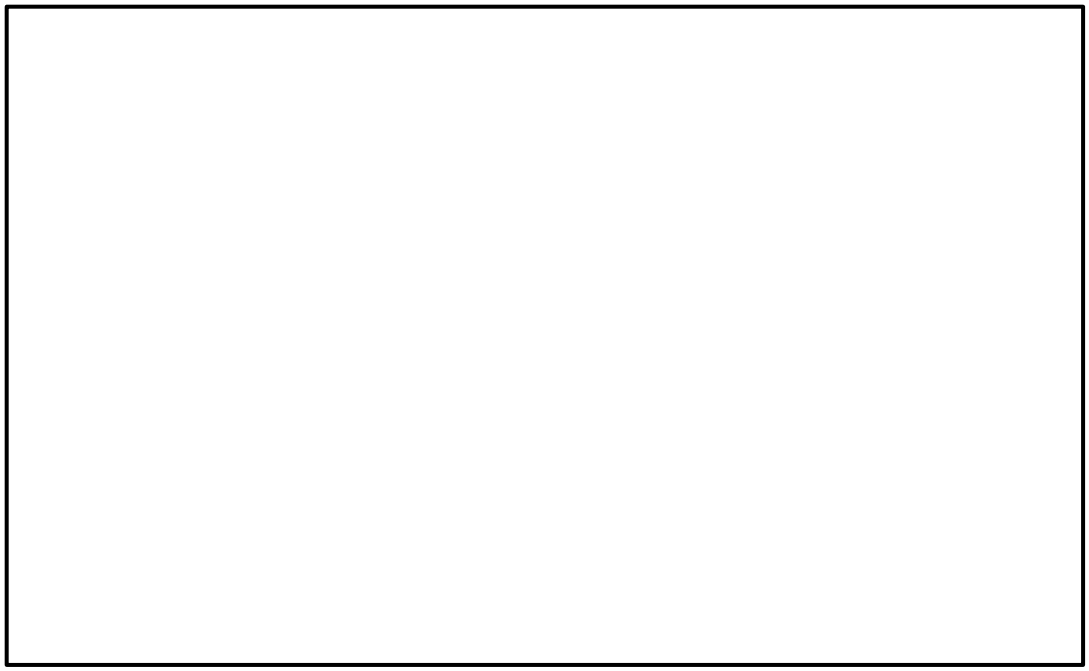

FIGURE 30. Incidence of voids (%) among different restorative groups.

FIGURE 31. Images show internal voids. (a), (b) samples from XF group; (c), (d) samples from FSU group; (e), (f), (g) samples from TEC group; (h), (i) samples from QX group.

DISCUSSION

RBC materials are often considered the restorative material of choice in various clinical situations due to their unique qualities including their esthetic properties and the ability to bond to the tooth structure which makes them one of the most conservative filling materials.[1] Although RBC materials have properties that meet some clinical requirements, they have some less desired properties. One of the main challenges facing the RBC materials is polymerization shrinkage that produces stress at the tooth-restoration interface that may clinically lead to the formation of marginal and internal gaps. Several studies have been done addressing the clinical relevance of this phenomenon with using in-vitro microleakage. However, these studies have generally evaluated the correlation between polymerization shrinkage and microleakage of the marginal gap rather than the internal adaptation.[112-116]

The goals of this study were to quantitatively evaluate the internal adaptation among different bulk-fill RBC materials and a traditional RBC placed incrementally and to evaluate aging effect on the internal adaptation. Measuring the gap area between the restorative material and the tooth structure has been used as the representative index for the internal adaptation. In this study five different filling materials were compared and to produce accurate measurements, it was important that every experimental step be detailed and precise.

There are many factors influencing the stress formation including volumetric polymerization shrinkage, elastic modulus, curing mode used, configuration factor of the

restoration, and adherence of the resin composite to the cavity walls.[117] In the current study, the cavity size and type, dentin adhesive, and curing method were standardized across all specimens; only the RBC material was varied.

Longitudinal clinical trials have a great scientific influence on determining the efficiency of restorative materials. On the other hand, they are time consuming and demand a large sample size that is challenging to be uniform and standardized. Thus, laboratory studies simulating the clinical condition are vital as an alternative prospect.

There are critical factors to be considered in the experimental procedures. First, the variable nature of tooth substrate needs to be considered. Bonding to tooth structure can be influenced by structural defects like the presence of internal crazes and enamel cracks. Considering that hydrated teeth have shown better bonding than dried teeth,[118] using extracted teeth that were stored and manipulated using different conditions might affect the highly variable nature of the results. Also, the anatomical features like cusp height and shape had an effect on the final cavity preparation dimensions and C-factor, which impact the resulted data. This was the motivation for using the Lathe in this study that allowed the secured handpiece to be precisely moved, preparing the experimental teeth while they were stationary. The attached measuring wheels allowed repeating the desired cavity dimensions successfully.

Second, some complications might follow the physical sectioning method that was used in this study to make the margin visible for examination that includes time consuming and the destructive nature of the procedure. Several methods have attempted to evaluate internal adaptation of RBC materials to tooth structure. Using a non-destructive technique like micro computed tomography (micro-CT or μCT) might be

advantageous in avoiding destruction to the samples. Numerous studies were done using micro-CT after silver nitrate infiltration to evaluate the internal adaptation of RBC materials.[119-121] Another study investigated Class I cavity floor internal adaptation by using swept-source optical coherence tomography (OCT) in combination with microtensile bond strength (MTBS) using different filling methods.[122] Nevertheless, using these new methods to investigate internal adaptation have some significant challenges including; time intensive, high cost, technically challenging, steep learning curve, the results obtained from them need to be validated by sectioning the specimens and examining them under a stereomicroscope. In many cases during the result validation process and in which silver nitrate had previously penetrated the gap, it is very difficult to detect an other dye like rhodamine because of the intense black shade of the silver nitrate that could interfere with the detection of the red rhodamine shade.[121]

Some previous studies utilized the dye and tracer penetration methods to determine the quality of material internal adaptation and the existence of gaps.[111-123] These methods necessitate soaking the specimens in various types of solutions, sectioning through the restorations, and evaluating the leakage that occurred by light microscopy. SEM can also be used to examine the resin/dentin interface after sectioning specimens.[124] Tracers, such as methylene blue, erythrosine, rhodamine, and silver nitrate, can be used for penetration. This technique is widely used due to its simplicity but it is very technique sensitive, a more subjective evaluation, and it has restraints in quantitative assessment.[125,126] Another way for assessing internal adaptation is to measure the fluid flow from the pulp area to a sealed dentin surface.[127,128] An additional method used for leakage detection is immersing the restored tooth in water and exposing the tooth to air

pressure. In this case, gap existence is confirmed if bubbles appear due to gas passage through the gap. This non-destructive method results in nominal values that mostly are too low and the definite leakage path is unclear. In addition, leakage could happen through the dental substrate itself that can lead to a false increase of leakage values.[110]

In this study, the dependent variables of gap measurement, sum of all gap categories, and cavity adaptation (%) were ranked (from smallest to largest) prior to analyses process. This step was necessary due to non-normality of the obtained data that would have had the potential to affect the study results. Although the study data were trending toward significant results, and given that the study had 80-percent power, a larger sample size could be advantageous to increase the study power.

The first research alternative hypothesis was that there is significantly better internal adaptation among a traditional RBC material placed incrementally compared to bulk-fill RBC materials. The research findings supported this hypothesis, as there was a significant difference in the gap measurement and the sum of all gap categories for the control group FSU (incrementally placed) compared to the other bulk-fill material gap measurements, TEC, SF, and XF (Figure 27). Of materials tested in bulk placement, all had a significantly larger gap interfaces than the incrementally placed one, with the exception of QX material. For this material, there was no statistical difference found between it and the FSU group. However, QX showed smaller gap than SF in regards to the sum of all gap categories ($p = 0.0257$).

The smaller number of measured gap area indicates less space between the tooth structure and the restorative material that would affect the incidence and severity of post-operative pain or sensitivity following placement of the restorative material. Likewise,

material adaptation to the cavity floor plays an important role in the resultant sensitivity as shown in this study that FSU group had the highest cavity adaptation rate among all other bulk-fill composite materials except QX group (Figure 28).

Factors that impact polymerization shrinkage include monomer molecular weight and concentration and filler size and concentration.[129] FSU, TEC, QX, and XF all have higher filler content by weight % than SF (Table III). These high-filler resin composites have a lower monomer content to contribute to the polymerization process related to the lower polymerization shrinkage. While the space occupied by the filler particles does not contribute to the curing contraction, high filler particle loads may necessitate low-molecular-weight monomers to ensure a proper handling viscosity. In low viscosity materials, the motility of the monomers is active, such that a greater proportion of monomers contribute in the polymerization procedure, increasing the polymerization shrinkage.[19] In the present study, SF exhibited significantly larger gaps and less adaptation to the cavity compared with the other materials tested. The fact it had the least filler content aided in lowering its viscosity via sonic activation during placement but resulted in generating more polymerization shrinkage. However, in previous studies authors claimed that the SonicFill material showed excellent adaptation to cavity walls due to the vibration during placement. This, in turn, resulted in smaller gaps and fewer voids when compared with conventionally lined and layered composite placement techniques.[29,130]

In general, FSU showed less gap area measurements and higher material adaptation to the cavity floor than the other restorative materials. This result is supported by a recent study that stated the usage of the universal composite in conjunction with an

increment-fill technique improved the adaptation of the composite to the cavity floor compared with a bulk-fill technique.[122] This outcome might be related to the reduced material volume and C-factor of each increment which as a result reduced the polymerization shrinkage and generated contraction stresses which are in agreement with previously reported studies on the advantages of incremental filling.[131,132]

In this study, the gaps had been classified into three categories based on their location (CA: gap at the composite/adhesive interface; AD: gap at the adhesive/dentin interface; CAD: gap at the composite/adhesive/dentin interface (mixed)). AD and CAD gap categories could have a clinical significance on the post-operative sensitivity occurrence due to the bare dentinal surface. Nevertheless, the restorative material poor retention and eventually loss occurrence could be linked to the CA gap category especially when it is associated with a poor marginal retention. Obviously in this study, the incidence and measurement of the CA gap category was significantly higher than the others, followed by AD. Another finding of interest in the results of this experiment is that the SF group had the highest incidence of CA gap compared with the other groups. It is not clear why this occurred, even though the same bonding system was used for all the experiment groups. It might be connected with relatively higher polymerization shrinkage in SonicFill restorative material that produced gap between the restorative material and the bonding agent. Also, it might be connected with the poor chemical reaction between SonicFill restorative material and OptiBond Solo Plus bonding system used in this study although they were from the same company (Kerr, West Collins, Orange, CA). Further study will be necessary comparing the SonicFill restorative material capability to adapt to the cavity pulpal floor using different total-etch adhesive systems (OptiBond XTR,

OptiBond Solo Plus, OptiBond All-In-One, OptiBond FL, and OptiBond XTR; Kerr, West Collins, Orange, CA, USA). The CA gap category could be clinically significant in relation to the composite material retention and long-term service.

The second research alternative hypothesis suggested that there is significantly better internal adaptation among a traditional RBC material placed incrementally compared with bulk-fill RBC materials not-aged versus aged. This hypothesis was partially accepted. To examine the alterations at the interface between resin restorations and tooth cavities, three manners of artificial aging technique can be used: 1) aging by water storage; 2) aging by thermocycling; and 3) aging by thermomechanical load cycling.[133-135] The aging technique used in this study was selected based on a previous study demonstrating that applying a thermocycling aging procedure created stresses similar to those seen with six months in the clinical situation, and it would therefore be a clinically relevant method.[110] It is interesting to note, the aging technique used in this study appeared to be a significant factor affecting the resultant gap size measurement while it did not affect the material adaptation to the cavity (Figure 25). This indicates that the aging method that used in this study affected the existing gap size by making them worse. Yet, the aging techniques did not assist in gap generation. Several previous studies showed that thermocycling or storage in water might have slight effect on artificial aging; however, thermomechanical load cycling can efficiently cause artificial aging.[110,126,136,137]

Another study investigating the effect of the three various types of aging techniques on gap size and bulk-fill material adaptation is recommended.

In this study, the internal adaptation concept was evaluated in four different locations within the same tooth; as three slices obtained from each tooth allowed analysis

of four different sides (a, b, b', and c). According to the results, the sum of all gap categories for slice sides a and c (the mesial and the distal slice sides) was significantly larger than b (one of the middle slice sides) ($p \leq 0.0155$). In other words, the gaps located closer to the center of the cavity were larger than those located close to the cavity sides. This implies that the material adaptation to the cavity margin was better when there were more walls to bond to.

Of the materials tested in this study, all had at least one cohesive failure that was associated with the dentin or the composite material except SF. The XF group had the highest incidence of cohesive failure that all occurred in the composite material (Table VI). This might be linked directly to the material strength and properties.

A void within the composite material is a pore that remains unoccupied. It could result from an imperfection in the material processing and is generally deemed undesirable. It can impact the mechanical properties and lifespan of the composite. Voids can allow moisture to penetrate the composite material and contribute to anisotropy of the composite. Moreover, voids can act as a crack nucleation site which would be an issue because crack formation and propagation can generate unpredictable behavior of the material.[138] In this study, SF had the significantly lowest probability of voids among the groups ($p \leq 0.0024$). The second group with low probability of voids was QX ($p \leq 0.0287$) (Figure 30). The incidence of voids can be related to the viscosity of the material during placement and the placement technique. A resin composite material with a high viscosity will likely generate voids in the composite more than a low viscosity material. It is challenging for a high viscosity resin or matrix to penetrate the original void spaces among adjacent fillers. This will produce voids to form close the filler surface.

Preventing these voids becomes more challenging when the fillers are packed tightly together in a composite.[139] The current study supported these data as it showed fewer voids associated with SF that had a low viscosity during placement in response to sonic activation. Furthermore, it had been suggested that using an increment-fill placement technique would result with more voids due the nature of the layering procedure that would allow air to trap between layers. In this study, although FSU (the incrementally placed group) showed a statistical higher probability of voids compared with SF and QX, there was no statistically significant difference comparing it to the other two bulk-fill groups (i.e. TEC and XF).

SUMMARY AND CONCLUSIONS

The objectives of this study were to quantitatively evaluate the internal adaptation among different bulk-fill RBC materials and a traditional RBC placed incrementally by measuring the gap area between the restorative material and the tooth structure and to evaluate aging effect on the internal adaptation. Four bulk-fill RBC materials and one placed incrementally were tested.

Within the limitations of this in vitro study that included limited material selection, the following conclusions can be drawn:

FSU had the smallest sum off all gap category values compared to the bulk-fill materials tested except QX. However, QX had significant smaller values than SF.

FSU had the smallest gap measurement values compared to the bulk-fill materials tested except QX and TEC. No significant difference was exhibited among the other restorative groups.

The CA gap location had the highest incidence and gap size values of all investigated categories.

All aged groups had greater gap values in regards to the sum of all gap categories and gap measurement compared to non-aged groups. However, no significant difference was found between aged and non-aged groups in correlation to the cavity adaptation.

XF material had the highest cohesive failure among all groups except for SF that had no cohesive failure at all.

All the tested restorative materials had voids inside the material except SF that had no voids at all.

Based on the results of the present study, it can be concluded that incrementally placed material FSU had the highest internal adaptation to the cavity surface. In general, the four materials placed using the same bulk-fill technique show various behaviors and results. Moreover, thermocycling aging technique influenced the existing gap quantities but it didn't play a role in the material adaptation to the cavity.

Clinical significance: based on the results of this study, an increment-fill technique seems to have significant advantages in internal adaptation over a bulk-fill technique.

REFERENCES

1. Schneider LF, Cavalcante LM, Silikas N. Shrinkage stresses generated during resin-composite applications: a review [published online ahead of print September 30, 2009]. J Dent Biomech doi: 10.4061/2010/131630.

2. Pashley DH. Dynamics of the pulpo-dentin complex. Crit Rev Oral Biol Med 1996;7(2):104-33.

3. Lutz F, Krejci I, Barbakow F. Quality and durability of marginal adaptation in bonded composite restorations. Dent Mater 1991;7(2):107-13.

4. Lee MR, Cho BH, Son HH, Um CM, Lee IB. Influence of cavity dimension and restoration methods on the cusp deflection of premolars in composite restoration. Dent Mater 2007;23(3):288-95.

5. Alomari QD, Reinhardt JW, Boyer DB. Effect of liners on cusp deflection and gap formation in composite restorations. Oper Dent 2001;26(4):406-11.

6. Park J, Chang J, Ferracane J, Lee IB. How should composite be layered to reduce shrinkage stress: incremental or bulk filling? Dent Mater 2008;24(11):1501-05.

7. Rullmann I, Schattenberg A, Marx M, Willershausen B, Ernst CP. Photoelastic determination of polymerization shrinkage stress in low-shrinkage resin composites. Schweiz Monatsschr Zahnmed 2012;122(4):294-9.

8. Tiba AZ, Zeller GG, Estrich CG, Hong A. A laboratory evaluation of bulk-fill versus traditional multi-incrementfill resin-based composites. ADA Prof Prod Rev 2013;8:13-26.

9. Karthick K, Kailasam S, Geetha Priya PR. Polymerization shrinkage of composites–a review. J Indian Acad Dent Specialists 2011;2(2):32-3.

10. Puckett A, Fitchie J, Hembree JJr, Smith J. The effect of incremental versus bulk fill techniques on the microleakage of composite resin using a glass-ionomer liner. Oper Dent 1991;17(5):186-91.

11. El-Safty S, Silikas N, Watts DC. Creep deformation of restorative resin-composites intended for bulk-fill placement. Dent Mater 2012;28(8):928-35.

12. Kwon Y, Ferracane J, Lee IB. Effect of layering methods, composite type, and flowable liner on the polymerization shrinkage stress of light cured composites. Dent Mater 2012;28(7):801-9.

13. Roggendorf MJ, Kramer N, Appelt A, Naumann M, Frankenberger R. Marginal quality of flowable 4-mm base vs. conventionally layered resin composite. J Dent 2011;39(10):643-7.

14. Lazarchik DA, Hammond BD, Sikes CL, Looney SW, Rueggeberg FA. Hardness comparison of bulk-filled/transtooth and incremental-filled/occlusally irradiated composite resins. J Prosthet Dent 2007;98(2):129-40.

15. Czasch P, Ilie N. In vitro comparison of mechanical properties and degree of cure of bulk fill composites. Clin Oral Investig 2013;17(1):227-35.

16. Ferracane JL. Developing a more complete understanding of stresses produced in dental composites during polymerization. Dent Mater 2005;21(1):36-42.

17. Taha NA, Palamara JE, Messer HH. Cuspal deflection, strain and microleakage of endodontically treated premolar teeth restored with direct resin composites. J Dent 2009;37(9):724-30.

18. Van Ende A, Mine A, De Munck J, Poitevin A, Van Meerbeek B. Bonding of low-shrinking composites in high C-factor cavities. J Dent 2012;40(4):295-303.

19. Davidson CL, Feilzer AJ. Polymerization shrinkage and polymerization shrinkage stress in polymer-based restoratives. J Dent 1997;25(6):435-40.

20. Campodonico CE, Tantbirojn D, Olin PS, Versluis A. Cuspal deflection and depth of cure in resin-based composite restorations filled by using bulk, incremental and transtooth-illumination techniques. J Am Dent Assoc 2011;142(10):1176-82.

21. Emmler J, Seiss M, Kreppel H, Reichl FX, Hickel R, Kehe K. Cytotoxicity of the dental composite component TEGDMA and selected metabolic by-products in human pulmonary cells. Dent Mater 2008;24(12):1670-75.

22. Moorthy A, Hogg CH, Dowling AH, Grufferty BF, Benetti AR, Fleming GJ. Cuspal deflection and microleakage in premolar teeth restored with bulk-fill flowable resin-based composite base materials. J Dent 2012;40(6):500-5.

23. Dentsply International. Surefil® SDR™ flow product brochure. Available at: http://www.surefilsdrflow.com/sites/default/files/SureFil_Brochure.pdf. Accessed August 22, 2013.

24. Kerr. SonicFill Sonic-Activated, Bulk Fill Composite System product brochure. Available at: http://www.kerrdental.com/cms-filesystem-action?file=/kerrdental-products-brochure/sonicfillsalessheet.pdf. Accessed January 21, 2014.

25. Bechtold J, Dos Santos PJ, Anido-Anido A, Di Hipólito V, Alonso RC, D'Alpino PH. Hardness, polymerization depth, and internal adaptation of Class II silorane composite restorations as a function of polymerization protocol. Eur J Dent 2012;6(2):133.

26. Buonocore M. A simple method of increasing the adhesion of acrylic filling materials to enamel surfaces. J Dent Res 1955;34(6):849-53.

27. Bowen RL. Properties of a silica-reinforced polymer for dental restorations. J Am Dent Assoc 1963;66:57-64.

28. Ferracane JL, Ferracane LL, Braga RR. Effect of admixed high-density polyethylene (HDPE) spheres on contraction stress and properties of experimental composites. J Biomed Mater Res B Appl Biomater 2003;66(1):318-23.

29. Ferracane JL. Resin composite--state of the art. Dent Mater 2011;27(1):29-38.

30. FDI World Dental Federation. World Health Organization. Consensus statement on dental amalgam. FDI World 1995;4(4):9-10.

31. Hickel R. Die zervikale füllung. Dtsch Zahnärzt Z 1994;49(11):13-9.

32. Hickel R, Manhart J, Garcia-Godoy F. Clinical results and new developments of direct posterior restorations. Am J Dent 2000;13(Spec No):41D-54D.

33. Hickel R, Manhart J. Longevity of dental restorations in posterior teeth and reasons for failure. J Adhesive Dent 2001;3:45-64.

34. Roulet JF, Reich T, Blunck U, Noack M. Quantitative margin analysis in the scanning electron microscope. Scanning Microsc 1989;3(1):147-58; discussion 58-9.

35. Roulet JF. Marginal integrity: clinical significance. J Dent 1994;22 Suppl 1:S9-12.

36. Roulet JF. Benefits and disadvantages of tooth-colored alternatives to amalgam. J Dent 1997;25:459-73.

37. Roulet JF. Longevity of glass ceramic inlays and amalgam--results up to 6 years. Clin Oral Investig 1997;1(1):40-6.

38. Eakle W, Ito R. Effects of insertion technique on microleakage in mesioocclusodistal composite resin restorations. Quintessence Int 1990;21:369-74.

39. Tyas M. Clinical performance of two dentin adhesives: 2-year results. Aust Dent 1996;41:324-27.

40. Duncalf WV, Wilson NH. A comparison of the marginal and internal adaptation of amalgam and resin composite restorations in small to moderate-sized Class II preparations of conventional design. Quintessence Int 2000;31(5):347-52.

41. Sano H, Takatsu T, Ciucchi BJAH, Horner JA, Matthews WG, Pashley DH. Nanoleakage: Leakage within the hybrid layer. Oper Dent 1994;20(1):18-25.

42. Sano H, Kanemura N, Burrow MF, Inai N, Yamada T, Tagami J. Effect of operator variability on dentin adhesion: students vs. dentists. Dent Mater J 1998;17(1):51-8.

43. Tay FR, Gwinnett AJ, Pang KM, Wei SH. Variability in microleakage observed in a total-etch wet-bonding technique under different handling conditions. J Dent Res 1995;74(5):1168-78.

44. Tay FR, Gwinnett JA, Wei SH. Micromorphological spectrum from overdrying to overwetting acid-conditioned dentin in water-free acetone-based, single-bottle primer/adhesives. Dent Mater 1996;12(4):236-44.

45. Tay FR, Gwinnett AJ, Wei SH. Ultrastructure of the resin-dentin interface following reversible and irreversible rewetting. Am J Dent 1997;10(2):77-82.

46. Pashley DH, Ciucchi B, Sano H, Horner JA. Permeability of dentin to adhesive agents. Quintessence Int 1993;24(9):618-31.

47. Pashley DH, Ciucchi, B, Sano H, Carvalho RM, Russell CM. Bond strength versus dentine structure: a modelling approach. Arch Oral Biol 1995;40(12):1109-18.

48. Pashley DH, Sano H, Ciucchi B, Yoshiyama M, Carvalho RM. Adhesion testing of dentin bonding agents: a review. Dent Mater 1995;11(2):117-25.

49. Pashley DH, Tay FR. Aggressiveness of contemporary self-etching adhesives. (Pt 2). Etching effects on unground enamel. Dent Mater 2001;17(5):430-44.

50. Penschke A, Blunck U, Roulet JF. Influence of incorrect application of Optibond FL on the marginal adaptation of Class V restorations. Am J Dent 2000;13(5):239-44.

51. Nakabayashi N, Nakamura M, Yasuda N. Hybrid layer as a dentin-bonding mechanism. J Esthet Dent 1991;3(4):133-8.

52. Nakabayashi N, Ashizawa M, Nakamura M. Identification of a resin-dentin hybrid layer in vital human dentin created in vivo: durable bonding to vital dentin. Quintessence Int 1992;23(2):135-41.

53. Nakabayashi N, Pashley DH. Hybridization of dental hard tissues. Quintessence Publishing (IL) 1998:20-30.

54. Watanabe I, Nakabayashi N, Pashley DH. Bonding to ground dentin by a phenyl-P self-etching primer. J Dent Res 1994;73(6):1212-20.

55. Xu HC, Liu WY, Wang T. Measurement of thermal expansion coefficient of human teeth. Aust Dent J 1989;34(6):530-5.

56. Xu HH, Martin TA, Antonucci JM, Eichmiller FC. Ceramic whisker reinforcement of dental resin composites. J Dent Res 1999;78(2):706-12.

57. Xu HH, Moreau JL, Sun L, Chow LC. Novel CaF(2) nanocomposite with high strength and fluoride ion release. J Dent Res 2010;89(7):739-45.

58. Xu HH, Quinn JB, Smith DT, Giuseppetti AA, Eichmiller FC. Effects of different whiskers on the reinforcement of dental resin composites. Dent Mater 2003;19(5):359-67.

59. Xu HH, Schumacher GE, Eichmiller FC, Peterson R, Antonucci J, Mueller H. Continuous-fiber preform reinforcement of dental resin composite restorations. Dent Mater 2003;19(6):523-30.

60. Xu HH, Sun L, Weir MD, Antonucci J, Takagi S, Chow L, Peltz M. Nano DCPA-whisker composites with high strength and Ca and PO(4) release. J Dent Res 2006;85(8):722-7.

61. Xu HH, Weir MD, Sun L, Moreau J, Takagi S, Chow L, Antonucci J. Strong nanocomposites with Ca, PO(4), and F release for caries inhibition. J Dent Res 2010;89(1):19-28.

62. Loguercio AD, Reis A, Hernandez PA, Macedo RP, Busato AL. 3-Year clinical evaluation of posterior packable composite resin restorations. J Oral Rehabil 2006;33(2):144-51.

63. Leinfelder KF, Bayne SC, Swift Jr EJ. Packable composites: overview and technical considerations. J Esthet Dent 1999;11(5):234-49.

64. Sturdevant JR, Bayne, SC, Wilder AD, Heymann HO, Lisk M, Foster E. Three-year clinical study of a failed condensable posterior composite. J Dent Res 1993;72:380.

65. Bayne SC, Thompson JY, Swift Jr EJ, Stamatiades P, Wilkerson M. A characterization of first-generation flowable composites. J Am Dent Assoc 1998;129(5):567-77.

66. Lee IB, Min SH, Kim SY, Ferracane J. Slumping tendency and rheological properties of flowable composites. Dent Mater 2010;26(5):443-8.

67. Chuang SF, Liu JK, Chao CC, Liao FP, Chen YH. Effects of flowable composite lining and operator experience on microleakage and internal voids in Class II composite restorations. J Prosthet Dent 2001;85(2):177-83.

68. Behle C. Flowable composites: properties and applications. Pract Periodontics Aesthet Dent 1998;10(3):347, 50-1.

69. Hervas-Garcia A, Martinez-Lozano MA, Cabanes-Vila J, Barjau-Escribano A, Fos-Galve P. Composite resins. A review of the materials and clinical indications. Med Oral Patol Oral Cir Bucal 2006;11(2):E215-20.

70. Olmez A, Oztas N, Bodur H. The effect of flowable resin composite on microleakage and internal voids in Class II composite restorations. Oper Dent 2004;29(6):713-9.

71. Andersson-Wenckert I, Sunnegardh-Gronberg K. Flowable resin composite as a Class II restorative in primary molars: A two-year clinical evaluation. Acta Odontol Scand 2006;64(6):334-40.

72. Lindberg A, van Dijken JW, Horstedt P. In vivo interfacial adaptation of Class II resin composite restorations with and without a flowable resin composite liner. Clin Oral Investig 2005;9(2):77-83.

73. Ernst CP, Cortain G, Spohn M, Rippin G, Willershausen B. Marginal integrity of different resin-based composites for posterior teeth: an in vitro dye-penetration study on eight resin-composite and compomer-/adhesive combinations with a particular look at the additional use of flow-composites. Dent Mater 2002;18(4):351-8.

74. Szep S, Frank H, Kenzel B, Gerhardt T, Heidemann D. Comparative study of composite resin placement: centripetal buildup versus incremental technique. Pract Proced Aesthet Dent 2001;13(3):243-50; quiz 52.

75. Miguez PA, Pereira PN, Foxton RM, Walter R, Nunes MF, Swift Jr EJ. Effects of flowable resin on bond strength and gap formation in Class I restorations. Dent Mater 2004;20(9):839-45.

76. Yearn JA. Factors affecting cure of visible light activated composites. Int Dent J 1985;35(3):218-25.

77. Podshadley AG, Gullett CE, Crim G. Interface seal of incremental placement of visible light-cured composite resins. J Prosthet Dent 1985;53(5):625-6.

78. Davidson CL, de Gee AJ, Feilzer A. The competition between the composite-dentin bond strength and the polymerization contraction stress. J Dent Res 1984;63(12):1396-9.

79. Feilzer AJ, De Gee AJ, Davidson CL. Increased wall-to-wall curing contraction in thin bonded resin layers. J Dent Res 1989;68(1):48-50.

80. Flury S, Hayoz S, Peutzfeldt A, Husler J, Lussi A. Depth of cure of resin composites: is the ISO 4049 method suitable for bulk fill materials? Dent Mater 2012;28(5):521-8.

81. Ilie N, Hickel R. Investigations on a methacrylate-based flowable composite based on the SDR technology. Dent Mater 2011;27(4):348-55.

82. Moorthy A, Hogg CH, Dowling AH, Grufferty BF, Benetti AR, Fleming GJP. Cuspal deflection and microleakage in premolar teeth restored with bulk-fill flowable resin-based composite base materials. J Dent 2012;40(6):500-05.

83. Ernst CP, Meyer GR, Muller J, Stender E, Ahlers MO, Willershausern B. Depth of cure of LED vs QTH light-curing devices at a distance of 7 mm. J Adhes Dent 2004;6(2):141-50.

84. Vandewalle KS, Ferracane JL, Hilton TJ, Erickson RL, Sakaguchi RL. Effect of energy density on properties and marginal integrity of posterior resin composite restorations. Dent Mater 2004;20(1):96-106.

85. You C, Xu X, Burgess JO. Depth of cure of core-build material with three different curing lights [abstract 1736]. J Dent Res 2001;80:252.

86. Braga RR, Hilton TJ, Ferracane JL. Contraction stress of flowable composite materials and their efficacy as stress-relieving layers. J Am Dent Assoc 2003;134(6):721-28.

87. Labella R, Lambrechts P, Van Meerbeek B, Vanherle G. Polymerization shrinkage and elasticity of flowable composites and filled adhesives. Dent Mater 1999;15(2):128-37.

88. Ikeda I, Otsuki M, Sadr A, Nomura T, Kishikawa R, Tagami J. Effect of filler content of flowable composites on resin-cavity interface. Dent Mater J 2009;28(6):679-85.

89. Fleming GJ, Awan M, Cooper PR, Sloan AJ. The potential of a resin-composite to be cured to a 4mm depth. Dent Mater 2008;24(4):522-9.

90. Burgess J, Cakir D. Comparative properties of low-shrinkage composite resins. Compend Contin Educ Dent 2010;31 Spec No 2:10-5.

91. Van Noort R, Barbour ME. Introduction to dental materials. 4th ed. Edinburgh: Mosby Elsevier, 2013.

92. Zidan O, Hill G. Phosphoric acid concentration: enamel surface loss and bonding strength. J Prosthet Dent 1986;55(3):388-92.

93. Nakabayashi N, Kojima K, Masuhara E. The promotion of adhesion by the infiltration of monomers into tooth substrates. J Biomed Mater Res 1982;16(3):265-73.

94. Fusayama T. Factors and prevention of pulp irritation by adhesive composite resin restorations. Quintessence Int 1987;18(9):633-41.

95. Cao L, Geerts S, Gueders A, Albert A, Seidel L, Charpentier J. Experimental comparison of cavity sealing ability of five dental adhesive systems after thermocycling. J Adhes Dent 2003;5(2):139-44.

96. Kanca J. A method for bonding to tooth structure using phosphoric acid as a dentin-enamel conditioner. Quintessence Int 1991;22(4):285-90.

97. Kanca J, 3rd, Suh BI. Pulse activation: reducing resin-based composite contraction stresses at the enamel cavosurface margins. Am J Dent 1999;12(3):107-12.

98. Gwinnett AJ, Kanca JA. Micromorphology of the bonded dentin interface and its relationship to bond strength. Am J Dent 1992;5(2):73-7.

99. Vallittu PK. The effect of void space and polymerization time on transverse strength of acrylic-glass fibre composite. J Oral Rehabil 1995;22(4):257-61.

100. Vallittu PK. Case report: a glass fibre reinforced composite resin bonded fixed partial denture. Eur J Prosthodont Restor Dent 2001;9(1):35-8.

101. Vallittu PK, Narva K. Impact strength of a modified continuous glass fiber--poly(methyl methacrylate). Int J Prosthodont 1997;10(2):142-8.

102. Vallittu PK, Sevelius C. Resin-bonded, glass fiber-reinforced composite fixed partial dentures: a clinical study. J Prosthet Dent 2000;84(4):413-8.

103. Vallittu PK. Survival rates of resin-bonded, glass fiber-reinforced composite fixed partial dentures with a mean follow-up of 42 months: a pilot study. J Prosthet Dent 2004;91(3):241-6.

104. Heraeus Kulzer. Venus® bulk fill product information. Available at: http://webmedia.kulzer-dental.com/media/hkg/downloads_new/venus_5/venus_bulk_fill_1/Venus_Bulk_Fill_Kids_Produktinformation_GB.pdf. Accessed July 21, 2015.

105. Carvalho RM, Pereira JC, Yoshiyama M, Pashley DH. A review of polymerization contraction: the influence of stress development versus stress relief. Oper Dent 1996;21(1):17-24.

106. Leinfelder KF. Posterior composite resins: the materials and their clinical performance. J Am Dent Assoc 1995;126(5):663-4, 67-8, 71-2 passim.

107. McCullock AJ, Smith BG. In vitro studies of cusp reinforcement with adhesive restorative material. Br Dent J 1986;161(12):450-2.

108. Ilie N, Hickel R. Shrinkage behaviour of novel flowable composites based on the SDR™-technology. Dent Mater 2010;26(2):e130.

109. Ruiz J, Mitra S. Using cavity liners with direct posterior composite restorations. Compend Contin Educ Dent 2006;27(6):347.

110. De Munck J, Van Landuyt K, Peumans M, Poitevin A, Lambrechts P, Braem M, Van Meerbeek B. A critical review of the durability of adhesion to tooth tissue: methods and results. J Dent Res 2005;84(2):118-32.

111. Furness A, Tadros MY, Looney SW, Rueggeberg FA. Effect of bulk/incremental fill on internal gap formation of bulk-fill composites. J Dent 2014;42(4):439-49.

112. Rosin M, Urban AD, Gartner C, Bernhardt O, Splieth C, Meyer G. Polymerization shrinkage-strain and microleakage in dentin-bordered cavities of chemically and light-cured restorative materials. Dent Mater 2002;18(7):521-8.

113. Braga RR, Ferracane JL, Condon JR. Polymerization contraction stress in dual-cure cements and its effect on interfacial integrity of bonded inlays. J Dent 2002;30(7-8):333-40.

114. Peutzfeldt A, Asmussen E. Determinants of in vitro gap formation of resin composites. J Dent 2004;32(2):109-15.

115. Calheiros FC, Sadek FT, Braga RR, Cardoso PE. Polymerization contraction stress of low-shrinkage composites and its correlation with microleakage in Class V restorations. J Dent 2004;32(5):407-12.

116. Gerdolle DA, Mortier E, Droz D. Microleakage and polymerization shrinkage of various polymer restorative materials. J Dent Child (Chic) 2008;75(2):125-33.

117. Condon JR, Ferracane JL. Assessing the effect of composite formulation on polymerization stress. J Am Dent Assoc 2000;131(4):497-503.

118. Suliman AH, Boyer DB, Lakes RS. Polymerization shrinkage of composite resins: comparison with tooth deformation. J Prosthet Dent 1994;71(1):7-12.

119. Kim HJ, Park SH. Measurement of the internal adaptation of resin composites using micro-CT and its correlation with polymerization shrinkage. Oper Dent 2014;39(2):E57-70.

120. Kwon OH, Park SH. Evaluation of internal adaptation of dental adhesive restorations using micro-CT. Restor Dent Endod 2012;37(1):41-9.

121. Han SH, Park SH. Micro-CT evaluation of internal adaptation in resin fillings with different dentin adhesives. Restor Dent Endod 2014;39(1):24-31.

122. Bakhsh TA, Sadr A, Shimada Y, Mandurah M, Hariri I, Alsayed E, Tagami J, Sumi Y. Concurrent evaluation of composite internal adaptation and bond strength in a Class-I cavity. J Dent 2013;41(1):60-70.

123. Hilton TJ. Can modern restorative procedures and materials reliably seal cavities? In vitro investigations. (Pt 2). Am J Dent 2002;15(4):279-89.

124. Dionysopoulos D, Papadopoulos C, Koliniotou-Koumpia E. The evaluation of various restoration techniques on internal adaptation of composites in Class v cavities. Int J Biomater 2014;2014:148057.

125. Alani AH, Toh CG. Detection of microleakage around dental restorations: a review. Oper Dent 1997;22(4):173-85.

126. Heintze S, Forjanic M, Cavalleri A. Microleakage of Class II restorations with different tracers--comparison with SEM quantitative analysis. J Adhes Dent 2008;10(4):259-67.

127. Bouillaguet S, Duroux B, Ciucchi B, Sano H. Ability of adhesive systems to seal dentin surfaces: an in vitro study. J Adhes Dent 2000;2(3):201-8.

128. Del-Nero MO, Escribano N, de la Macorra JC. Analysis of sealing vs tensile bond strength of eight adhesive restorative material systems. J Adhes Dent 2000;2(2):117-27.

129. Braga RR, Ballester RY, Ferracane JL. Factors involved in the development of polymerization shrinkage stress in resin-composites: a systematic review. Dent Mater 2005;21(10):962-70.

130. Munoz-Viveros C, Yazici AR, Agarwal I, Campillo-Funollet M. Microleakage in Class II preparations restored with the SonicFill System. Poster session presented at: AADR/CADR Annual Meeting & Exhibition, 2012; Tampa, FL.

131. Chikawa H, Inai N, Cho E, Kishikawa R, Otsuki M, Foxton RM. Effect of incremental filling technique on adhesion of light-cured resin composite to cavity floor. Dent Mater J 2006;25(3):503-8.

132. Nikolaenko SA, Lohbauer U, Roggendorf M, Petschelt A, Dasch W, Frankenberger R. Influence of c-factor and layering technique on microtensile bond strength to dentin. Dent Mater 2004;20(6):579-85.

133. Shono Y, Terashita M, Shimada J, Kozono Y, Carvalho RM, Russell CM, Pashley DH. Durability of resin-dentin bonds. J Adhes Dent 1999;1(3):211-8.

134. Leloup G, D'Hoore W, Bouter D, Degrange M, Vreven J. Meta-analytical review of factors involved in dentin adherence. J Dent Res 2001;80(7):1605-14.

135. Nikaido T, Kunzelmann KH, Chen H, Ogata M, Harada N, Yamaguchi S, Cox CF, Hickel R, Tagami J. Evaluation of thermal cycling and mechanical loading on bond strength of a self-etching primer system to dentin. Dent Mater 2002;18(3):269-75.

136. Abdalla AI, Davidson CL. Effect of mechanical load cycling on the marginal integrity of adhesive Class I resin composite restorations. J Dent 1996;24(1-2):87-90.

137. Mitsui FH, Bedran-de-Castro AK, Ritter AV, Cardoso PE, Pimenta LA. Influence of load cycling on marginal microleakage with two self-etching and two one-bottle dentin adhesive systems in dentin. J Adhes Dent 2003;5(3):209-16.

138. Hull D, Clyne TW. An introduction to composite materials. Cambridge University Press, 1996.

139. Shakya N, Roux JA, Jeswani AL. Effect of resin viscosity in fiber reinforcement compaction in resin injection pultrusion process. Appl Compos Mater 2013;20(6):1173-93.

ABSTRACT

QUANTITATIVE COMPARISON OF INTERNAL ADAPTATION BETWEEN BULK-FILL AND TRADITIONAL MULTI-INCREMENT-FILL RESIN-BASED COMPOSITE MATERIALS

by

Fatema Sabri Alqudaihi

Indiana University School of Dentistry,
Indianapolis, Indiana

BACKGROUND: Currently, incremental placement is the standard technique used to overcome limitations related to resin-based composite (RBC) material. However,

it has some drawbacks that affect its efficiency. Recently, many resin-based composite materials have been introduced to the market allowing for use of the bulk-fill technique with many advantages over the incremental placement technique. OBJECTIVES: To quantitatively evaluate the internal adaptation among different light-activated bulk-fill RBC materials and a traditional RBC placed incrementally by measuring the gap area between the restorative material and the tooth structure and to evaluate aging effect on the internal adaptation. METHODS: A Class I cavity with specific dimensions was prepared using 70 extracted human molar teeth. They were randomly distributed into five groups; four groups were restored with different resin-based composite systems using a bulk-fill technique (TEC, SF, QX, XF); the fifth group (the control) was restored with multi-increment-fill technique (FSU). Each group was divided equally and randomly into two groups; the first group was the control and the other was the aged group that was thermocycled. Then, each tooth was sectioned occluso-gingivally and three 2-mm thick slices were obtained. Digital images from all specimens were recorded and analyzed and the presence and dimension of gaps were measured. Data were analyzed using ANOVA with a 5-percent significance level. RESULTS: FSU had the smallest gap measurement values compared with the bulk-fill materials tested except QX and TEC ($p \leq 0.008$). FSU had the smallest sum of all gap category values compared with the bulk-fill materials tested, except QX ($p \leq 0.021$). QX was significantly smaller than SF ($p = 0.0257$). The CA gap location category had the highest incidence and gap size values. All aged groups had greater gap values in regard to the gap measurement and the sum of all gap categories compared with non-aged groups. CONCLUSION: The incrementally placed material FSU had the highest internal adaptation to the cavity surface while the other four

materials using the bulk-fill technique showed various behaviors and results. The thermocycling aging technique influenced the existing gap quantities. The findings suggest that the increment-fill technique has advantages in terms of internal adaptation over the bulk-fill technique.

CURRICULUM VITAE

Fatema Sabri Alqudaihi

February 1982	Born in Virginia, USA
June 1999	High School Diploma The Second Secondary School Qatif, Saudi Arabia
August 1999 to June 2005	Bachelor of Dental Medicine & Surgery (BDS), College of Dentistry, King Saud University, Riyadh, Saudi Arabia.
July 2005 to June 2006	Dental Internship Qatif Central Hospital Qatif, Saudi Arabia King Fahad Military Hospital Dhahran, Saudi Arabia
November 2006 to June 2012	Employee for Saudi Ministry of Health Qatif Central Hospital Qatif, Saudi Arabia
October 2007 to March 2010	Advanced Education in General Dentistry Program Resident Prince Abdulrahman Advanced Dental Institute, Riyadh, Saudi Arabia University of British Columbia Vancouver, Canada.
July 2012 to June 2015	Operative Dentistry Graduate Program Indiana University School of Dentistry Indianapolis, Indiana.
February 2015 to present	Adjunct Faculty, Restorative Department Indiana University School of Dentistry Indianapolis, IN

Professional Organizations

The Academy of Operative Dentistry
American Dental Education Association (ADEA)
American Academy of Cosmetic Dentistry
Saudi Dental Society
The Saudi Commission for Health Specialties