Cementing an Implant Crown: A Novel Measurement System Using Computational Fluid Dynamics Approach

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ABSTRACT

Background: Cementing restorations to implants is a widely used clinical procedure. Little is known about the dynamics of this process. Using a systems approach and advanced computing software modeling this can be investigated virtually. These models require validation against real-life models.

Purpose: The study aims to consider the system effect of a crown, abutment, and cement flow under different conditions and comparing real physical models to virtual computer simulations.

Materials and Methods: A physical model of implant abutments and crowns provided three groups according to abutment screw access modification ($n = 9$): open (OA), closed (CA), and internal vented (IVA) abutment groups. Crowns were cemented using standardized amounts and site application. Proportion of cement retained within the crown–abutment system was recorded and compared. Differences among groups were identified using analysis of variance (ANOVA) with Tukey's post hoc test ($\alpha \leq 0.05$). Three-dimensional multiphysics numerical stimulation software (STAR-CCM+, CD-adapco) with computational fluid dynamics (CFD) approach was applied to a virtual model system of a scanned abutment and crown system. Three-dimensional real-time model simulations of cement and air displacement were produced, evaluating cement application site, speed of crown seating, and abutment modifications.

Results: Statistically significant differences in cement retained within the system ($p < 0.01$) were found among the IVA > OA > OCA abutment groups. The CFD virtual simulations followed this trend. Site application and speed of seating also affected cement extrusion and cement marginal infill. Fast crown seating and occlusal cement site application produced air incorporation at the margins.

Conclusions: The CFD approach provides a convenient way to evaluate crown–cement–implant abutment systems with respect to cement flow. Preliminary evaluation indicates that the results achieved follow those of a physical actual cement-retained crown–implant abutment study.

KEY WORDS: abutments, computer-assisted, implant-supported crown, luting cement, peri-implantitis

INTRODUCTION

Before cementing a crown onto a tooth or an implant, it is essential to understand the differences between the periodontal tissue around a tooth and peri-implant tissues at both the histologic and clinical levels especially for their sealing abilities to prevent excess cement from penetrating subgingivally. In natural teeth, the nonkeratinized junctional epithelium attaches to the enamel and root surface via the internal basal lamina and desmosomes along the entire length of the junctional epithelium.[1] The dentogingival collagen fibers are firmly inserted into the cementum and the bone, and in a perpendicular or oblique direction, thus serving as a barrier to the epithelial migration and the impending bacterial invasion.[2] However, between the implant surface and the epithelial cells are hemi-desmosomes and basal lamina.[3] Fibers run a parallel course or in

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different directions to the implant surface.[4–6] Connective tissue cells and the collagen fiber bundles are separated from the oxide layer of titanium implant surfaces with a 20-nm-wide proteoglycan layer.[7] The connective tissue adhesion with implants has a weak mechanical resistance and provides poor protection as compared with the natural tooth.[8]

Implant crown cement application techniques for site and amount have been studied, indicating that this is being approached by the vast majority of clinicians in a somewhat arbitrary manner.[9] The implant manufacturers tend to base the abutment configurations on natural tooth form preparations developed decades ago. The focus on cement design has been related mainly to chemical composition, retentive properties, and ability to reduce dental caries in natural teeth.[10–12] The 2013 American Academy of Periodontology consensus report on peri-implant disease listed residual excess cement as a risk factor.[13] There is a need to provide systemic analysis for the cement-retained implant crown as a whole entity if there is to be a better understanding of how to optimize flow and limit the potential for disease as a result of cement extrusion from the system. For many clinicians, treatment planning cement-retained implant crown is the technique of choice due to factors such as: aesthetics, occlusal management, passive fit, ease of use, economics, and especially familiarity with cementation procedures.[14,15] The crown, implant abutment, and cement should be considered as a system, with each component contributing to how the system functions. Many cement formulations used in implant restoration are known to be non-Newtonian in nature and are subject to some peculiar effects such as shear thinning.[16,17] Such properties can have a potential influence on their behavior during seating a restoration, as the cement flow pattern alters with the forces applied. Knowledge of flow characteristics is a vital component of this cement-retained implant crown system. To better understand characteristics of dental cement flow, approaches based on a combination of in vitro test and virtual model simulation may prove useful.

Computational fluid dynamics (CFD) is a branch of fluid mechanics that solves and analyzes problems involving fluid flow by means of computer-based simulations.[18] Modern CFD technology allows complex numeric simulations. In medicine, these have been applied to the study of the cardiovascular system and enabled the evaluation of specific parameters, such as the velocity distribution of blood flow in the aorta, wall pressure, and wall shear stress on the aortic wall, which are very difficult to measure in vivo.[19] Recently, CFD has been used to show turbulence in the root canal during irrigation with different injection velocities.[20–22] No information of cement flow characteristics of cement-retained implant crown system has been studied. The purpose of this study was to evaluate cement flow in a cement-retained implant system and modeled flow using three-dimensional multiphysics numerical simulation software (STAR-CCM+, CD-adapco, Melville, NY, USA). Real-time virtual flow system models were developed. The objective of the simulations was to better understand the cement flow patterns during the seating of the crown, and to explore the effects of modifying the abutments and altering cement application techniques in this complex system.

MATERIALS AND METHODS

Retained Cement Measurement

Twenty-seven straight RC anatomic abutments and analogs for bone-level implants (Straumann USA, Andover, MA) were selected for evaluation. The abutments were tightened to 35 Ncm with a torque wrench onto individual analogs. To facilitate crown coping fabrication, the abutment screw access channel was partially filled with a 3-cm-long piece of polytetrafluoroethylene (PTFE) tape packed over the screw head.[23] The remainder of the screw access chamber was filled with resin material (Triad Tru Tray, Dentsply International Inc., York, PA) that was contoured to conform to the occlusal aspect of the abutment and light cured. Each of the abutment-analog complexes was numbered. A thin layer of wax lubricant (DVA Separator, Dental Venture of America, Corona, CA) was painted onto the abutments to act as a separator. The crown copings were fabricated by waxing directly to the metal abutment, as recommended by the manufacturer, and standardized by placing each abutment into a custom jig and injecting wax around it. Twenty-seven wax copings were made and inspected for uniformity. Following investing (Microstar HS, Jensen Dental, North Haven, CT) and casting in high noble porcelain bonding alloy (JP1, Jensen Dental), the cast copings were adjusted under 20× magnification to assist in adaptation to their corresponding abutments. The same technician fabricated all copings and verified the clinical acceptability of margins. The implant copings were numbered individually to conform to the number of the abutment analog that they were fabricated on. The 27 copings were then randomly assigned to one of three groups: (1) the control group: closed abutment (CA), in which the entire screw access channel was filled with the resin material; (2) the open abutment (OA) group, which had the original open screw access channel, but the PTFE tape was left over the screw head to simulate what would be done in clinical practice to allow access to the screw head; and (3) the internal vented abutment (IVA) group, which was similar to the OA group but featured the addition of two 1.50-mm diameter holes[24] placed 3 mm apical to the occlusal edge of the abutment, 180 degrees apart, to represent the mesial and distal proximal surfaces (Figure 1). To assist in orientation and reduce errors caused by rotation of the coping on the abutment, four 5-mm-long vertical marks (midfacial, lingual, and each proximal surface) were placed on the outer surface of each coping and on the corresponding position on the abutment apical to the margin. To measure seating discrepancy, the vertical height of the crown/abutment/analog complex (CAAC) was measured using a linear transducer device (Model GT2, Keyence Corp., Itasca, IL) capable of accuracy to within 0.5 µm. A custom jig was made to facilitate all measurements. After all the precementation, vertical measurements were made and recorded, and the CAACs were weighed with an analytical balance (Sartorius Secura 224-1S, Data Weighing Systems, Elk Grove, IL). TempBond NE cement (Kerr USA, Orange, CA) was selected and mixed according to the manufacturer's instructions and loaded into a 1.2-mL syringe with a fine tip (Ultradent Products Inc., South Jordan, UT). The cement loading and weighing procedures were mentioned in a previous study.[25] The weight of cement retained within the cemented CAAC was calculated by subtracting the cleaned cementation weight from the preseating weight.

CFD Simulation Model Construction

For the simulations, implant abutment and crown forms from scanned stereolithographic files provided data points for parameterization of the implant and reciprocating crown shapes, allowing for 50-µm die space[26,27] (Figure 2). The files were exported to a commercial CFD software (STAR-CCM+) for reprocessing. The STAR-CCM+ software has already been used in dentistry, evaluating endodontic irrigation techniques.[22] A polyhedral mesh was developed, utilizing the overset meshing technology available in STAR-CCM+ software to simulate the motion of the crown over the implant.[28] The approach used allows for relative movement of implant and crown without requiring morphing of the mesh. The volume of fluid (VOF) multiphase model was used to simulate the flow of cement in the system.[29] This model was particularly well suited for immiscible fluids such as cement and air as it enabled capturing the position and shape of the interface between the dental cement and surrounding air as the crown is seated. An adhesive resin cement (RelyX™ ARC cement, 3M ESPE, St. Paul, MN, USA) was selected and used in this study. Parameters related to its non-Newtonian fluid behavior were provided by the manufacturer and fluid properties were simulated by using the Herschel–Bulkley model for non-Newtonian fluids.[30] Series 3D animated simulations in real time were developed, then a cross-sectional cut through the overmesh showing volume fraction of cement was made. Cement site application, speed of

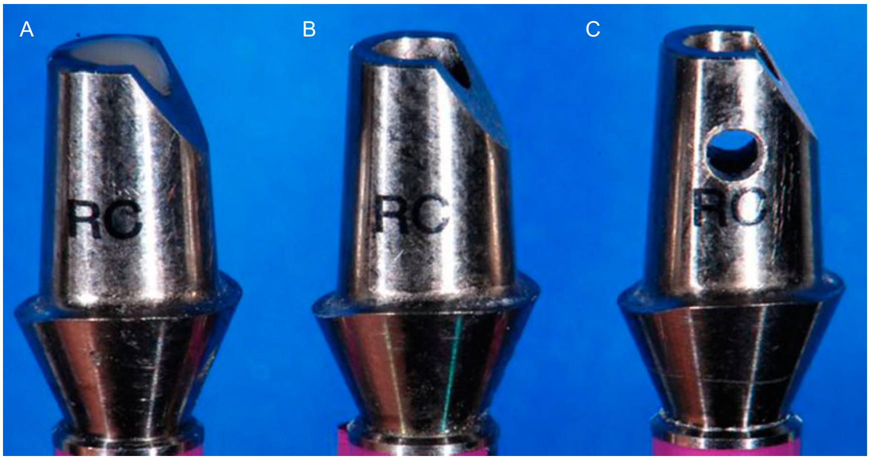

Figure 1 Abutment modifications: (A) closed abutment, CA; (B) open abutment, (OA); (C) internal vented abutment, IVA.

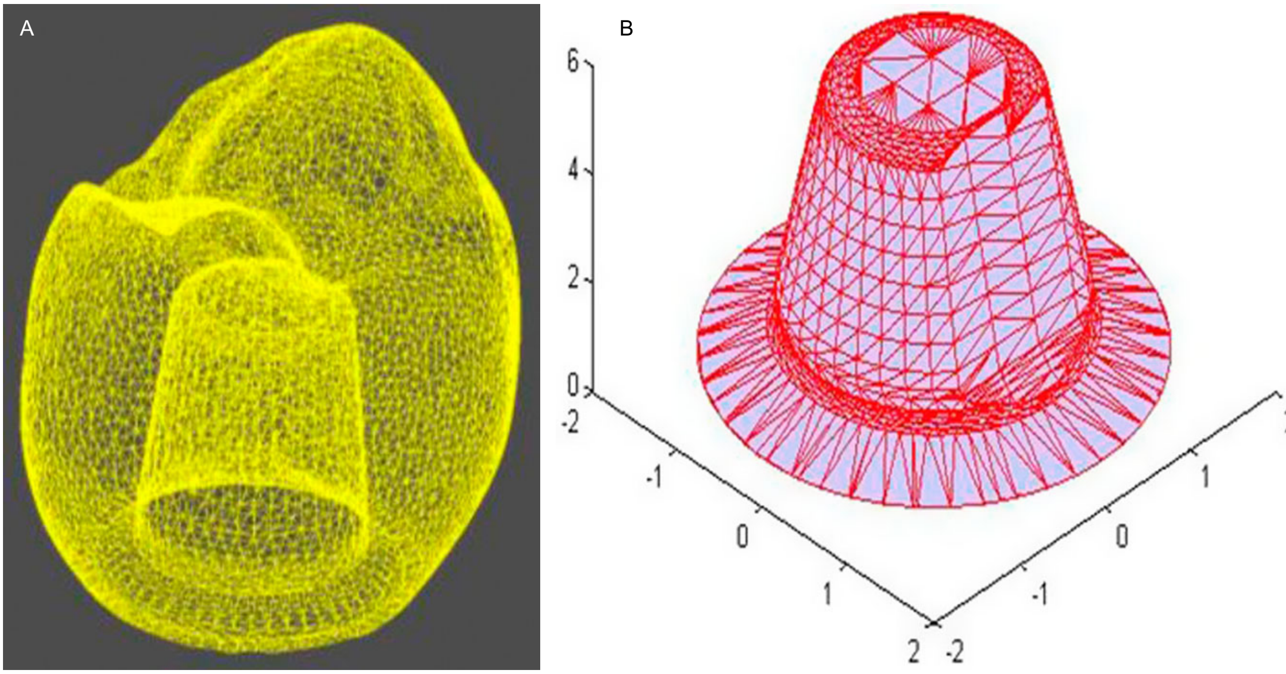

Figure 2 Stereolithographic files used to develop three-dimensional over mesh of crown (A) and polymeshed abutment (B).

seating the crown, and abutment modifications were simulated with cement flow pattern compared at specific sites and at specific times.

Cementation Application Site

There are a few studies on the most appropriate site to place cement within the crown to optimize flow.[31,32] The simulations of this study involved an abutment form with the screw access occluded (closed abutment) which represents the most common method for dealing with the screw channel.[33] The test cement application sites were a ½ toroid shape with a 1-mm radius placed at the crown margin compared with an occlusally positioned site. An arbitrary speed of seating the crown along the 7-mm abutment within 0.5 seconds was used. The simulation was stopped at three different positions to evaluate flow pattern. P1 represented start time of process. P2 was the first simulation to have cement extrude to beyond the cement margin of the crown. Both simulations were stopped at the same time frame for comparison. P3 was the final seating point of the crown. This site was evaluated for the volume fraction of cement to determine if the margin was sealed.

Speed of Seating

There are no references in the literature that describe the effect of seating speed on cement flow. Three speeds were arbitrarily chosen for the crown seating procedure in this study. Medium speed from P1 to P3 in 0.5 second is compared with slow speed from P1 to P3 in 1.0 second and fast speed from P1 to P3 in 0.25 second.

Abutment Modifications

Abutment modification and the effect on cement flow have been studied comparing the CA with OA and IVA.[25,34] Simulations were run using these abutment form parameters with medium speed for the crown seating.

Data Analysis

To evaluate the weight of cement retained within the cemented CAAC with different abutment systems, a one-way analysis of variance (ANOVA) was used to determine differences within groups, and the Tukey highly significant difference test (at $\alpha \leq 0.05$) was used to compute the differences between groups.

RESULTS

One-way ANOVA for the results of amount of cement retained within the cemented CAAC revealed that there were significant differences between the group means (df 2, MS 18346.04, F 88.58, $p < .0001$) (Table 1). The IVA group retained a statistically significant higher

TABLE 1 Summary of One-Way Analysis of Variance of Retained Cement Test

Source	SS	*df*	MS	*F*	*P*
Treatment (between groups)	36.692.08	2	18.346.04	88.58	<.0001
Error	4970.84	24	207.12		

amount of dental cement than the other groups ($p < .01$) (Figure 3).

Cement Site Application

Cement flow was simulated and evaluated when placed close to the crown margin (Figure 4, A–E), compared at positions P1, P2, and P3 to when cement was placed more occlusally (Figure 5, A–E). Differences were noted in the CA group when the cement was placed in the ½ toroid placed at the high occlusal site. At P2, the cement had already reached the outer confine of the crown margin; further seating extrudes cement from the system (Figure 5, D and E). By comparison, the cement flow was still well within the margin when the cement 1/2 toroid was initially placed near the margin of the crown. A color scheme was indicative of cement and air exchange within the cross section scheme (Figure 6). Red represents 100% cement volume, blue represents 100% air volume, with volume fraction of cement between represented by a color slide. Comparing the margin extrusion and seal at the final P3 position showed that more cement and less air are present when the cement loading site is near the crown margin (Figure 6).

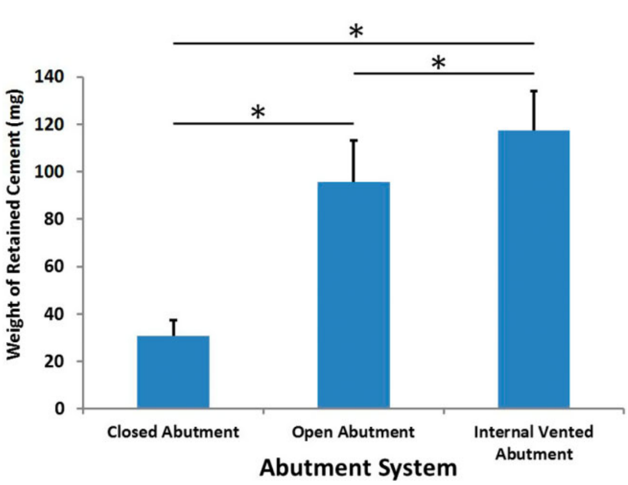

Figure 3 Weight of cement retained inside the coping/abutment/analog complex between different abutment systems. Vertical bars represent mean and standard deviation. Horizontal lines with * represent statistically significant at $p < .01$.

Speed of Seating the Crown

Slow, medium, and fast speed of crown seating for the time elapsed from P1 to P3 was evaluated for cement flow with the same cement amount and loading site, near to the crown margin. Medium speed from P1 to P3 in 0.5 second is compared with slow speed from P1 to P3 in 1.0 second and fast speed from P1 to P3 in 0.25 second (Figure 7). Increasing the speed of seating resulted in different marginal adaptation of cement (Figure 8), most especially with the 0.25-second seat, where air entrapment was noted.

Abutment Modifications Effects

Simulations using open and internal vented abutment designs were developed. Comparison of abutment design with CA, OA, and IVA when seating was carried under the conditions of cement placement at the crown margin is also represented (Figure 9). Figure 9B shows that the volume fraction of cement extrusion seen at the margin increased in order; CA > OA > IVA from position P1 to P3. Also, more air entrapment was seen in the screw access channel for the OA compared with the IVA.

DISCUSSION

In dentistry, some techniques have been developed over years of clinical use, often with little scientific data to support their efficacy. The fact that so many traditional techniques survive and are still in use gives testament to their clinical value. However, dentistry as a science is changing, with more and more of our processes becoming validated by investigation. One such area is the restoration of dental implants using cementation techniques. Dental implants are medical devices that behave very differently to the body part that they replace – namely, the tooth. The biological attachment mechanisms, depth of implant site, and behavior of cements all contributed to the vulnerability of dental implants.[1–8,10]

Although software has been used to predict fluid flow in dentistry, with STAR-CCM+ employed in a study evaluating irrigation of root canal system,[10] the authors are not aware of any studies that have looked at the fluid dynamics of cement during seating an implant crown. It is also considered that evaluating abutments form, crown form, and cements independently must be

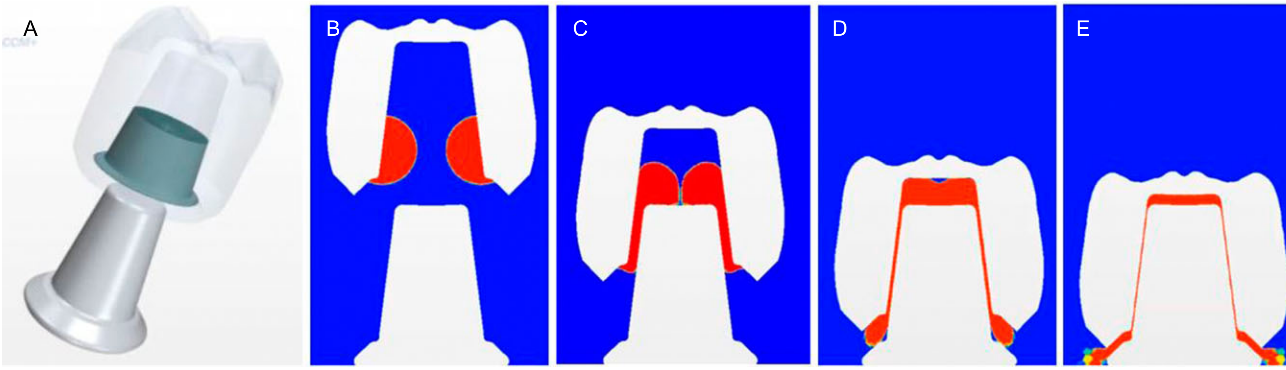

Figure 4 (A) Real-time flow system model developed using cement (1/2 toroid, 35 mm³ cement) loaded at crown margin. Cross-sectional cuts through still frame: cement placed at margin of crown (B); cementation at early stage (C); during seating (D); and completion of crown seating and simulation (E).

considered an oversight; these are individual units that together make a system. CFD is a common tool used by engineers to evaluate how a fluid-related system may respond under differing conditions.

The rheological properties of resin composite have been reported upon indicating that complex non-Newtonian dynamic behavior exists, related to composition and filler particle properties.[35,36] It is believed that cements have an internal structure that can be altered and rearranged by the application of shear forces during cementation, producing viscosity changes. During the cementation procedure, a dental crown seating over an

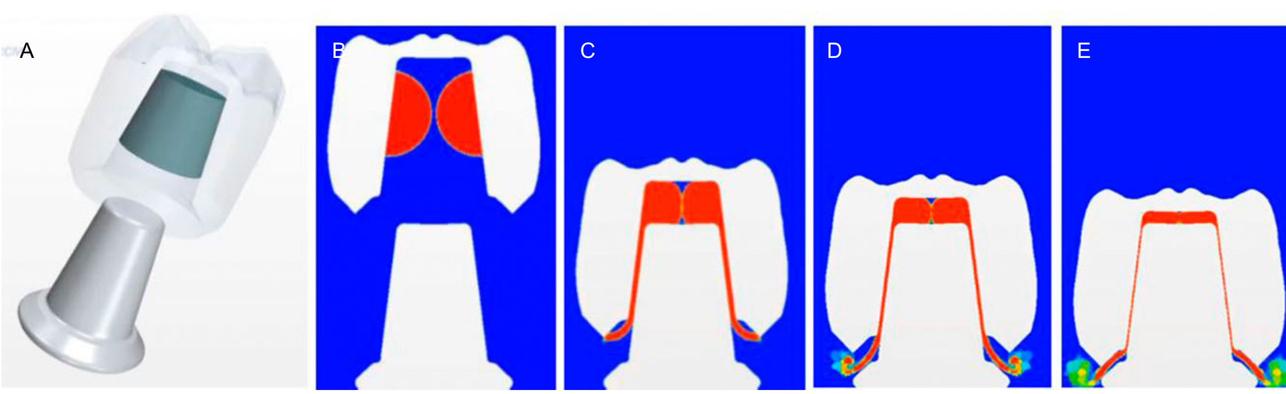

Figure 5 (A) Real-time flow system model developed using cement (1/2 toroid, 35 mm³ cement) loaded in the occlusal third of the crown. Cross-sectional cuts through still frame: cement placed at the occlusal third of crown internally (B); cementation at early stage (C); during seating (D); and completion of crown seating and simulation (E).

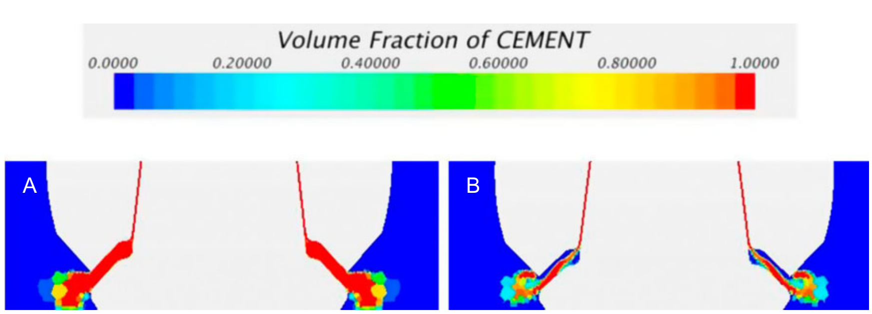

Figure 6 The top part is the volume fraction of cement, with red representing 100% of cement and blue comprises 100% of air. The bottom parts are the expanded views of complete simulation of crown margin region. (A) shows cement loaded at the crown margin and (B) at the occlusal third of crown internally.

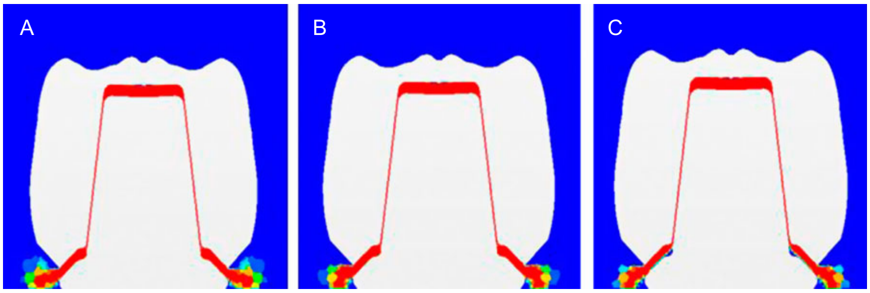

Figure 7 Completion of crown seating (A) at slow speed, 1.0 second; (B) at medium speed, 0.5 second; and (C) at fast speed, 0.25 second. Note incomplete cement infill at the crown margin region when seating at fast speed (C).

abutment will have different sites subject to differing shear forces. The cement would be expected to have related viscosity changes according to the speed, site, and volume of cement applied.

The virtual model used was a scan of an actual abutment representing a solid or closed screw access chamber. In vitro studies have proposed placement of cement at the margin site of the crown.[31,32] A survey confirmed that 17% of clinicians favored this location.[9] To test how site would affect cement flow, CFD data compared the application of a ½ toroid of cement placed within 1 mm of the margin of the crown versus the same

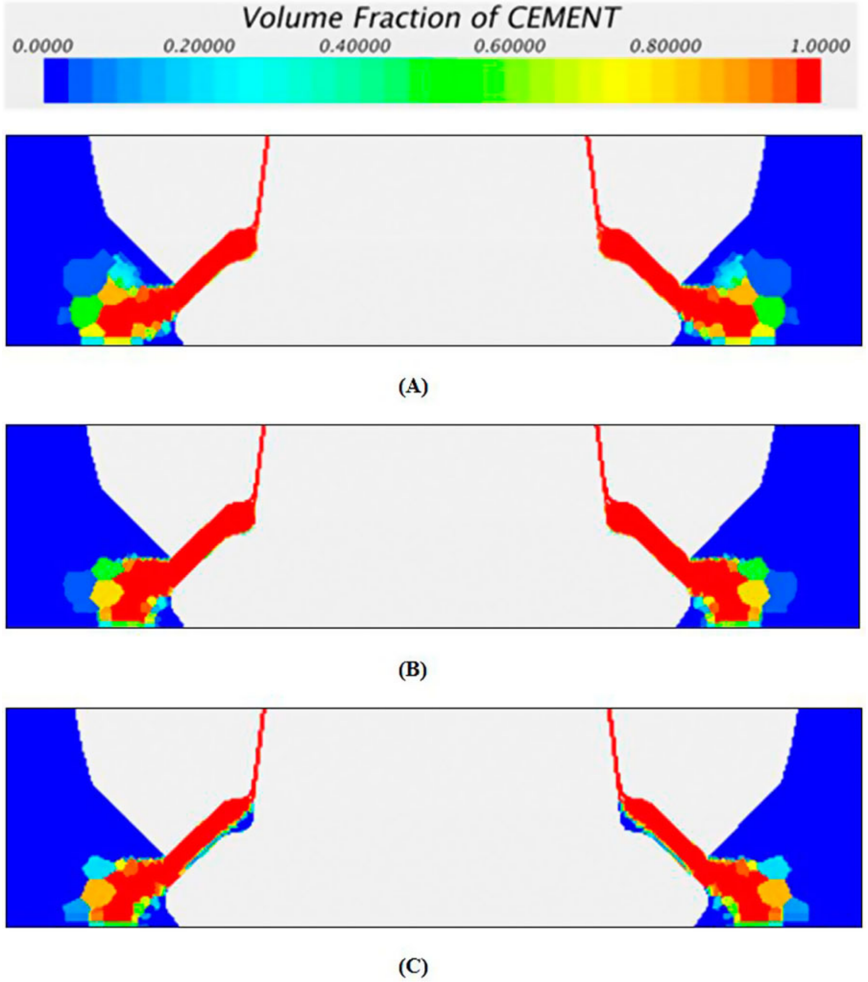

Figure 8 Enlarged images of the crown margin sites with seating speed (A) at slow speed, 1.0 second; (B) at medium speed, 0.5 second; and (C) at fast speed, 0.25 second, showing a difference in marginal volume fraction of cement, with fast-speed seating (C) trapping air significantly.

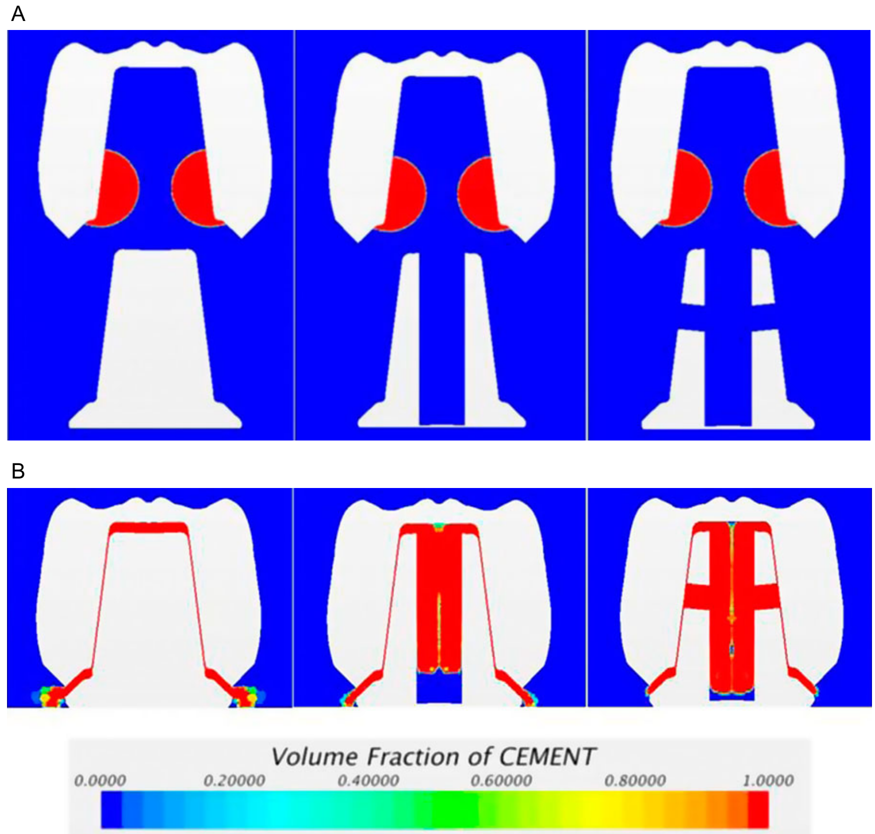

Figure 9 (A) Before seating the crown for closed abutment (left), open abutment (middle), and internal vented abutment (right). (B) After completing crown seating. Note margin fill, excess extrusion, and screw channel infill.

volume and shape applied near the occlusal surface. The real-time simulation showed that greater cement extrusion occurred and an incomplete margin seal was produced with the more occlusally placed cement. This is likely due to the cement placed closer to the occlusal surface having a greater volume being subjected to an initial compressive force much earlier as the crown seats (Figures 4C and 5C). The cement flowing down the axial walls would shear much earlier and flow through the margin too fast to provide a seal (Figures 5E and 6B).

Speed of seating a restoration has not been studied as far as the authors are aware. An arbitrary ideal speed of seating the crown along the 7-mm abutment within 0.5 second was chosen. When compared with twice the speed, differences were determined both in extrusion amount and incomplete fill around the crown margin (Figure 8C). It would appear that when the crown is quickly seated, the shear thinning properties of the cement cause too rapid a flow and create possibly incomplete sealing of margin.

Understanding how and where the cement will flow is of great value, especially when considering dental implants. Extrusion of cement is one example of where this would be of clinical value. Evaluating where the optimum site to place the cement and speed of seating the crown could have drastic effects on how much cement extrudes, how deep the cement flows, and how it changes the marginal cement adaptation. All of these factors could affect the life span of this system and have an impact on the health of the patient.

Model studies followed by in vivo investigations are the gold standard of dental research; however, these are very time consuming, controlling the variables across studies is difficult, and also expensive. CFD offers a faster, more convenient form of initial investigation which must then be further validated.

For this study, a preliminary validation is available. Abutment screw channel modifications evaluating cement have been studied in vitro in the physical form. The results of this CFD approach appear to replicate and confirm those results in many ways. The cement flow within both the real and simulated cement-retained crown-abutment system showed a greater extrusion of cement at the margins from OA and CA systems. Also, the internal screw access fill was different in both models, with the OA system having more air entrapment than the IVA system. It should be noted that the parameters of the physical study did not include speed of seating, which would greatly affect the behavior of cement. CFD also provides a means of evaluating flow velocity and pressure which could help determine if the forces provided by cement ejection could damage and penetrate into the peri-implant tissues during cementing procedures. It is hoped by further exploration of the implant abutment-crown-cement interactions on a systems level many help develop clinically useful data.

The clinical implications of this study are potentially far reaching. Computer studies allow greater control of the variables in this study: cement application site, speed of crown seating, and abutment modifications. By better understanding a systems approach, it is envisaged that reverse engineering may result with the form (shape of the abutment, cement site application, crown shape, etc.), all designed to optimize function. The results of this study suggest that crown cementation should involve the following: cement application at the margin of the crown in the shape of a ½ toroid, seating speed should be in the order of 14 mm/sec, inclusion of internal abutment vents alters cement flow resulting in less air entrapment and with a reduction of cement extrusion out of the margin.

Limitations of this in vitro study include the design of the crown/abutment/analog complex and CFD simulation model utilized in measuring cement flow during cementation. The lack of periodontal tissue simulation eliminates one important factor that may have an important effect on the flow pattern of cement that can occur in vivo.

CONCLUSIONS

Within the limitations of this study, the following conclusions may be drawn:

1. STAR-CCM+ software provides a convenient way to evaluate implant-abutment-cement systems with respect to cement flow.
2. Preliminary evaluation indicates that the virtual model simulation results achieved follow those of a physical actual cement-retained crown-implant abutment study.
3. The cement application site, abutment modifications, and speed of seating all have major effects on cement flow that may have clinical implications.

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