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Stress distribution in resin-based CAD-CAM implant-supported crowns

Pietro Ausiello [a], *Alessandro Espedito Di Lauro* [a], *João Paulo Mendes Tribst* [b,*], *David C. Watts* [c]

[a] School of Dentistry, University of Naples Federico II, via S. Pansini 5, 80131 Naples, Italy
[b] Academic Centre for Dentistry Amsterdam (ACTA), Department of Oral Regenerative Medicine, Universiteit van Amsterdam and Vrije Universiteit Amsterdam, 1081 LA Amsterdam, the Netherlands
[c] School of Medical Sciences and Photon Science Institute, University of Manchester, Manchester, UK

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ABSTRACT

Objective: This study aimed to evaluate the influence of new resin-based CAD-CAM implant-supported materials on posterior crown restoration stress and strain concentrations.
Methods: A previous 3D implant model was edited to receive a cement-retained posterior crown manufactured with different CAD/CAM materials (Estelite P Block, Estelite Block II or Estelite Layered Block). Each solid model was exported to the computer-aided engineering software and submitted to the finite element analysis of stress and strain. Material properties were assigned to each solid with isotropic and homogeneous behavior according to the manufacturer information. A vertical load of 600 N was applied in the occlusal region of the crown, via a simulated food bolus, and stress was calculated in Von Misses (σVM) for the implant, abutment and screw, Maximum (σMAX) Principal Stresses for the crown and microstrain for the bone.
Results: All simulated materials showed acceptable stresses levels with a similar stress pattern among the models. At the crown intaglio region and cement layer, however, differences were observed: Estelite P Block showed a lower tensile and shear stresses magnitude when compared to other resin-based materials with lower elastic modulus.
Significance: The stress effect of different resin-based CAD-CAM implant-supported crowns is predominant in the crown and cement layer, with Estelite P Block showing 7.4 % versus 9.3 % and 9.2 % for Estelite Block II and Estelite Layered Block of crown failure risk.

* Correspondence to: Department of Oral Regenerative Medicine, Academic Centre for Dentistry Amsterdam (ACTA), Universiteit van Amsterdam and Vrije Universiteit, Gustav Mahlerlaan 3004, 1081 LA Amsterdam, Noord-Holland, the Netherlands.
E-mail address: j.p.mendes.tribst@acta.nl (J.P.M. Tribst).

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1. Introduction

Restoring a missing tooth in the posterior area by a single implant supported crown has been indicated as the ideal dental therapy to preserve sound teeth and to distribute occlusal stresses optimally [1]. It helps to provide the patient with a long-term clinical life of rehabilitated teeth with proper esthetics and function. During the past decades metal-ceramic crown protocols have been extensively used in dentistry [2]. With the development of more resistant ceramics and the widespread availability of new resin composite materials, however, metallic crowns have lost popularity [3].

Monolithic materials have been developed to minimize the limits of metal-ceramic structures and to overcome costs, relative esthetics, extensive dental preparations and high stress distributions because of high Young's moduli of other materials – both metallic and polycrystalline [4]. These biomedical materials when perfectly integrated with dental implants exhibit, under occlusion, a different biomechanical behavior from natural teeth [5]. The absence of a periodontal ligament produces direct contact between the metallic implant and bone. Occlusal loads (forces) are now transmitted from the crown, via the implant rigid metallic structure, directly to the surrounding bone without the energy absorbing effect of the ligament [6]. When present, the periodontal ligament normally works like a spring and transduces the single masticatory intensive load into multiple vertical, horizontal and oblique lower intensity vectors [7]. Therefore, it exerts an important role in dispersing the original occlusal loading energy, avoiding stress at the implant-bone interface and limiting bone macrostrain and resorption [8]. This can only be partially reduced by the crown-material physical characteristics [9], mainly with limited elastic materials.

Computer-aided design (CAD) and computer-aided manufactured (CAM) resin-based composite blocks (RCB) are currently investigated for this situation as alternative materials to ceramic and metals in implant supported crowns [10]. Resin-based blocks (RCB) present new compositions consisting of an organic matrix and a high level of ceramic content that have been developed to resist and absorb stress in dental rehabilitation [11]. Further investigations are still necessary, especially for high occlusal-loading regions such as posterior teeth where implant supported crowns are subjected to specific occlusal stress distributions [10].

This study aimed to evaluate, by means of 3D Finite Elements Analysis, the mechanical behavior of implant supported crowns manufactured from resin-based CAD-CAM blocks. Numerical analysis using in silico investigation is widely used as biomechanical tool in dentistry as well as in general medicine to assess mechanical stress/strain phenomena occurring in hard dental tissues and in bone [11–17]. The research hypothesis was that the stiffness (E modulus) of implant-supported CAD-CAM molar crown would substantially affect stress and strain distributions during chewing loading.

2. Materials and methods

In the presented study, three resin-based CAD-CAM blocks were considered (Fig. 1).

The evaluated materials are produced from the same manufacturer (Tokuyama Dental Corporation, Tokyo, Japan), incorporating similar Supra-nano-size spherical fillers with high density. Nevertheless they exhibit different mechanical properties as summarized in Table 1. These materials are classified as Hybrid Resin blocks and allow the manufacture of esthetic CAD/CAM crowns (Fig. 2). However, they are not yet indicated for implant-supported restorations.

To simulate the indirect restoration, a previously created 3D CAD model of a sound molar was used. A lower molar was previously digitized with a high-resolution micro-CT scanner system (Bruker microCT) to generate the 3D shell [18]. The data sets were processed with InVesalius 3.1.1 software and 3D tessellated surfaces were generated with cross-section curves. Then, the parametric 3D model was created using loft surfaces. The final dimensions of the crown were 10.60 mm bucco-lingually and 12.36 mm mesio-distally.

The model was closed at the cervical region, and a Boolean difference was created between the crown and the abutment with a controlled thickness of 100 micrometers [18,19]. The space between crown and abutment was then used to create the cement layer model with a similar thickness.

A previously designed three-dimensional implant model (4.2 × 9 mm Xive, Dentsply-Sirona, Italy) was used to extract sharp edges and cross section curves [6]. The implant STP file was imported into the Computer Aided Design (CAD) software (Rhinoceros version 5.0 SR8, McNeel, Seattle, USA) and

Fig. 1 – CAD/CAM blocks simulated in the present study.

Table 1 – Materials properties considered in the present study.

Product name	Elastic modulus (GPa)	Flexural strength (MPa)
Estelite Block II	11.1	194
Estelite P Block	13.8	259
Estelite Layered Block	10.4	189

the NURBS (non-uniform rational B-spline) surfaces were created from the mesh generating a 3D volumetric model comparable to the real implant dimensions. The implant model presented a prosthetic-platform angulation of 0° [6].

From the research group database, a basic jawbone geometry was selected for the substrate simulation. For that, a simplified bone structure was modeled using a rectangular block [20]. Following the bone anatomy previously defined, the cortical bone tissue and medullary bone were considered separated volumes. The cortical was modeled with 1.0 mm uniform thickness.

To ensure a precise relationship at the *bone implant contact* (BIC,) a Boolean operation was made, by subtracting the implant from the bone model at the level of the crestal bone (Fig. 3). In total, the model was composed of cortical bone, trabecular bone, dental implant, prosthetic screw, cement layer, cylindrical abutment and resin-based crown. At the BIC, full-osseointegration of the implants was considered (Figs. 4, 5). Consequently, no relative movements between implant and bone were allowed.

The final solid volumetric model was imported into numerical software (ANSYS 19.2, ANSYS Inc., Houston, TX, USA) in STEP format. A 3D mesh was created using tetrahedral elements. To guarantee satisfactory precision of FEA results at the locations of interest, a mesh enhancement iterative process was used. Convergence of results was calculated to be achieved when the absolute estimations of stress (von-Mises) between two consecutive analyses were less than 10 %

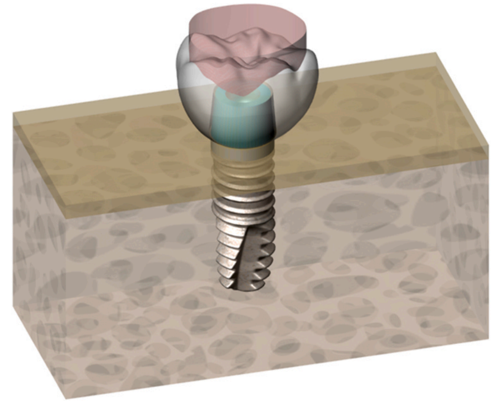

Fig. 3 – 3D model of the bone block with the implant model, resin-based crown and food bolus.

[21]. Elastic modulus and Poisson ratios for each material were given to each compact element, assuming linear elastic, isotropic and homogeneous behavior (Table 1).

Considering the boundary condition, a load of 600 N [21] was applied to simulate the occlusal force incident at the upper surface of the food bolus [13,18]. The load and fixation support were defined based upon a coordinate system that combined vectors on different axes of orientation x, y, z. The load was axially performed relative to the implant axis and the bone base was fixed in all direction [22].

In the present simulation, Von Mises Equivalent Stresses and Maximum Principal Stresses, produced by the loading forces, were assessed for the interpretation of results. Both criteria were used for quantitative comparison between the analyzed models according to the different crown materials. However, the stress peak has been plotted for quantitative comparison of each structure. In addition, for the crown, the failure risks were calculated as the ratio of *stress peak /tensile strength* for each material [23].

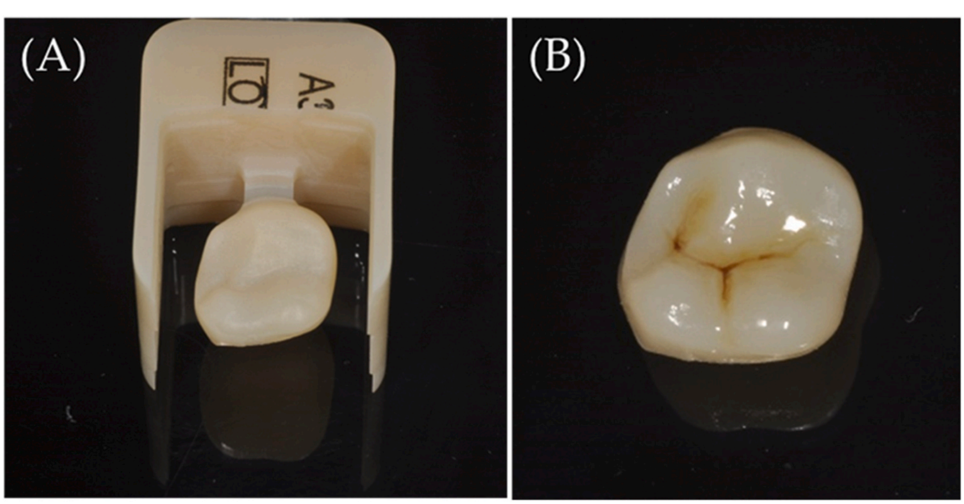

Fig. 2 – CAD/CAM resin-based crown manufactured with Estelite P Block. A) Milled restoration before esthetic characterization and B) after characterization and glaze (courtesy of Marco Amore).

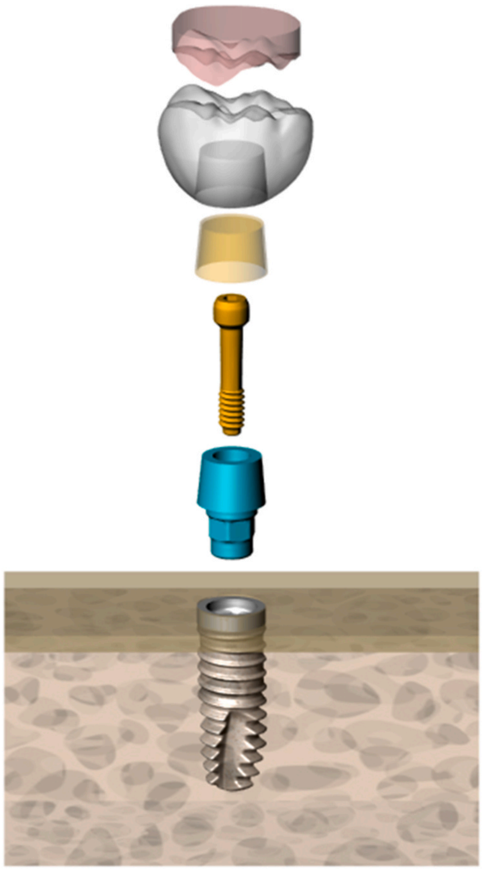

Fig. 4 – Discretized structures present in the 3D model showing the food bolus, crown, cement layer, prosthetic screw, abutment, implant, cortical and trabecular bone tissues.

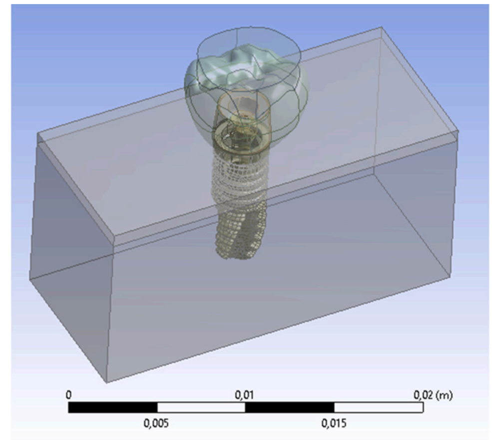

Fig. 5 – Numerical model imported to the computer aided engineering software.

3. Results

The convergence of Von Mises stress in the system was evaluated considering the previous boundary conditions. The initial moment up to 100% loading is presented in Fig. 6.

Based on the model, each condition was evaluated by von-Mises stress maps. Observing the section plane for the models, a similar stress pattern among the models is apparent without an obvious visual difference between them (Fig. 7). These stress maps were based upon a color-coded non-linear scale for stress. However, it is essentially a collective stress state, and it cannot be directly decoded into specific values of tensile, compressive or shear stress. Despite that, there was no apparent presence of contact loss between the structures or any non-uniform stress concentration.

After this initial evaluation, each region was separated and evaluated according to the stress distribution and peaks. Observing the section plane for the CAD/CAM crown, a similar stress pattern was apparent between the models with a slight difference in the intaglio region (Fig. 8). Evidently the lower the crown elastic modulus, the lower was the stress magnitude inside the crown.

Moreover, even more similar mechanical behavior was apparent for the stress distribution trend between the implant models, with the region of highest stress magnitude concentrated at the cervical level and implant platform (Fig. 9).

Similar to the implant structure, the abutment did not showed differences in mechanical response when the load was applied in the crown structure. For all three models, the region of highest stress magnitude was the abutment top surface and the region of the abutment/implant joint (Fig. 10).

Since the abutment and the implant showed no difference in the stress level when different crowns were simulated, the same was expected for the prosthetic screw. Indeed, observing Fig. 11, there is no difference between the simulated conditions, with the prosthetics screw demonstrating high stress near the first thread after the screw neck, regardless of the model.

Stress peaks were collected using the auto-tool max probe in the mechanical APDL software after processing the results. Table 2 summarizes the stress peaks collected for each structure. The crown was the structure with the lowest stress magnitude while the implant itself showed the highest stress. Herein, results in the cement layer were obtained using Maximum Principal Stress (tensile stress results in MPa). In addition, Maximum Shear Stress criteria were also calculated. Both criteria are associated with the bond strength and adhesive problems generated at the adhesive interface of indirect restorations. The failure risk of the restoration was calculated based in the ratio stress/strength. Estelite P Block showed 7.4 % versus 9.3 % and 9.2 % for Estelite Block II and Estelite Layered Block respectively (Fig. 12).

4. Discussion

The hypothesis was that the elastic modulus of implant-supported CAD-CAM molar crown would substantially affect stress and strain distribution during occlusal loading. The results showed that different models exhibited higher stresses along the adhesive interface with different

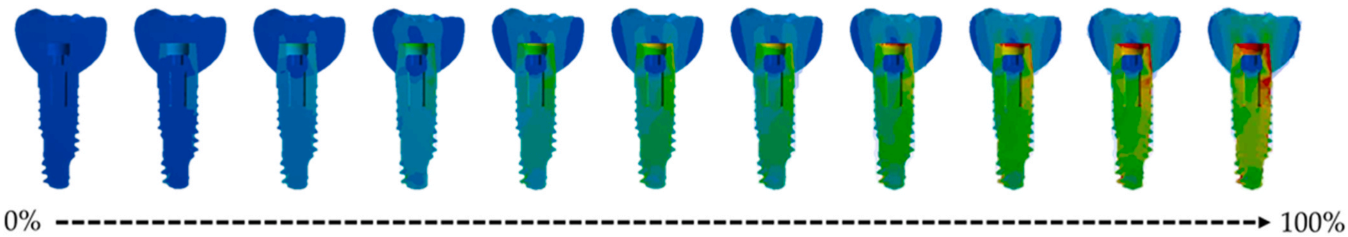

Fig. 6 – Setup during convergence test with 0–100 % of load application.

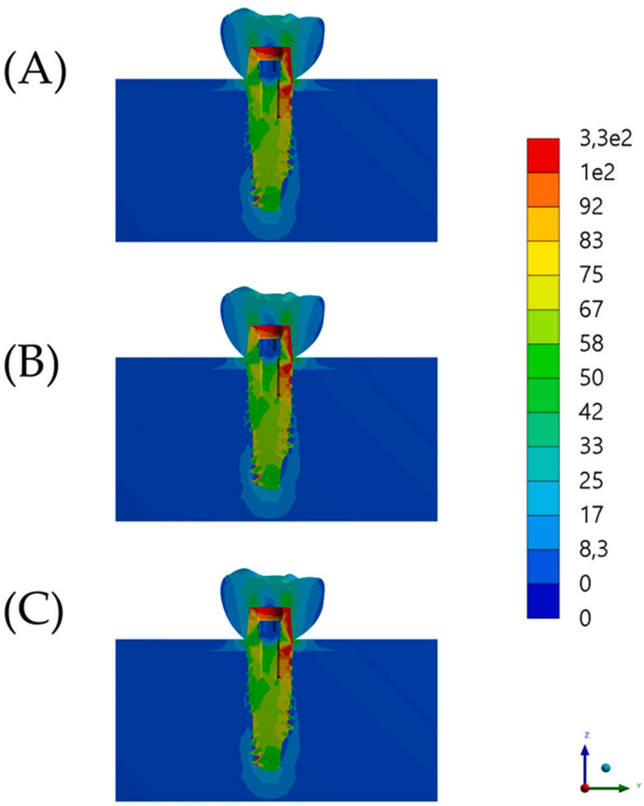

Fig. 7 – Section plane for von-Mises stress contour plots according to the different crown materials. A) Estelite Block II, B) Estelite P Block and C) Estelite Layered Block.

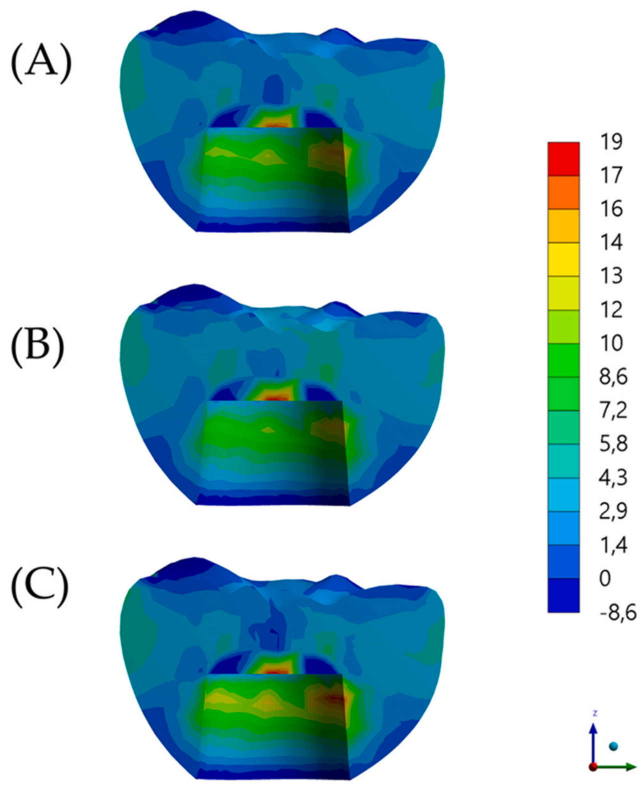

Fig. 8 – Section plane for Maximum Principal Stress contour plots for the crown according to the different materials. A) Estelite Block II, B) Estelite P Block and C) Estelite Layered Block.

magnitudes according to the restorative material simulated in the crown. Thus, the hypothesis was accepted.

Dental CAD/CAM allows the application of traceability in production lines, usage of stable manufacture of dental prostheses by means of reliable machining of homogeneous materials and reduced production time. In general, CAD/CAM materials used in restorations include ceramics and resin composites [24–26]. According to the literature, CAD/CAM hybrid composite blocks present the potential for enhancing mechanical properties to resist high biting forces [25,26]. The present study confirmed this viewpoint since low stress was observed when physiological chewing forces were simulated.

This improved mechanical behavior of hybrid composite blocks occurs owing to the association of resin matrix and filler particles that can be independently formulated in different blocks. Such variations may include the structure of the resin matrix, the ratio between matrix and fillers, the filler nanoparticle composition, sizes and shapes [24]. Many mechanical improvements were recently achieved by means of new industrial technologies applied to the resin matrix of

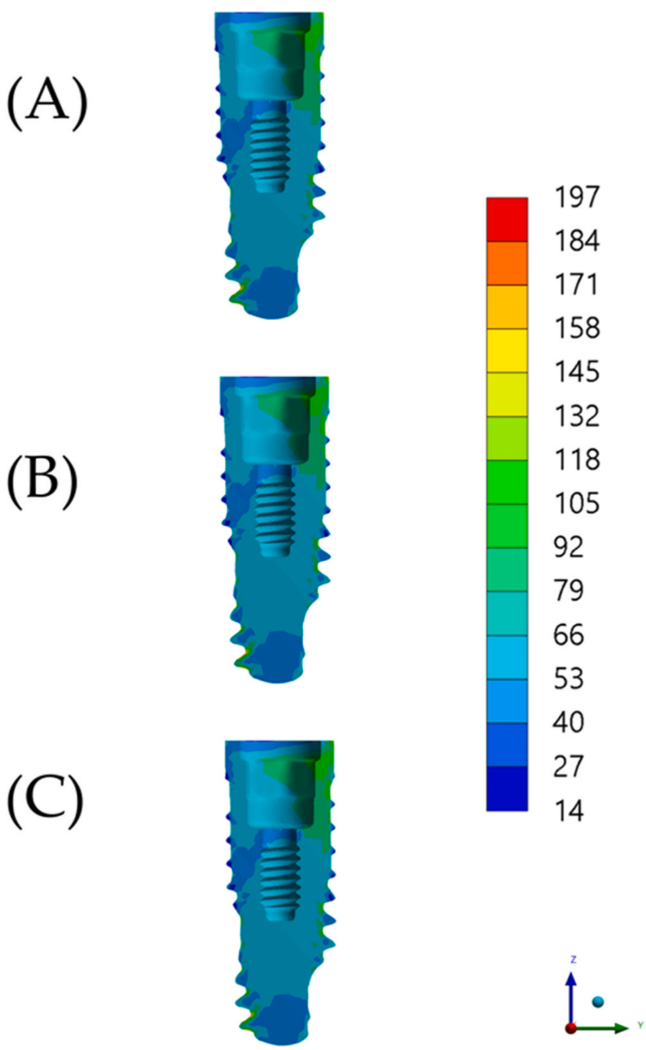

Fig. 9 – Section plane for von-Mises Stress contour plots for the implant according to the different crown materials. A) Estelite Block II, B) Estelite P Block and C) Estelite Layered Block.

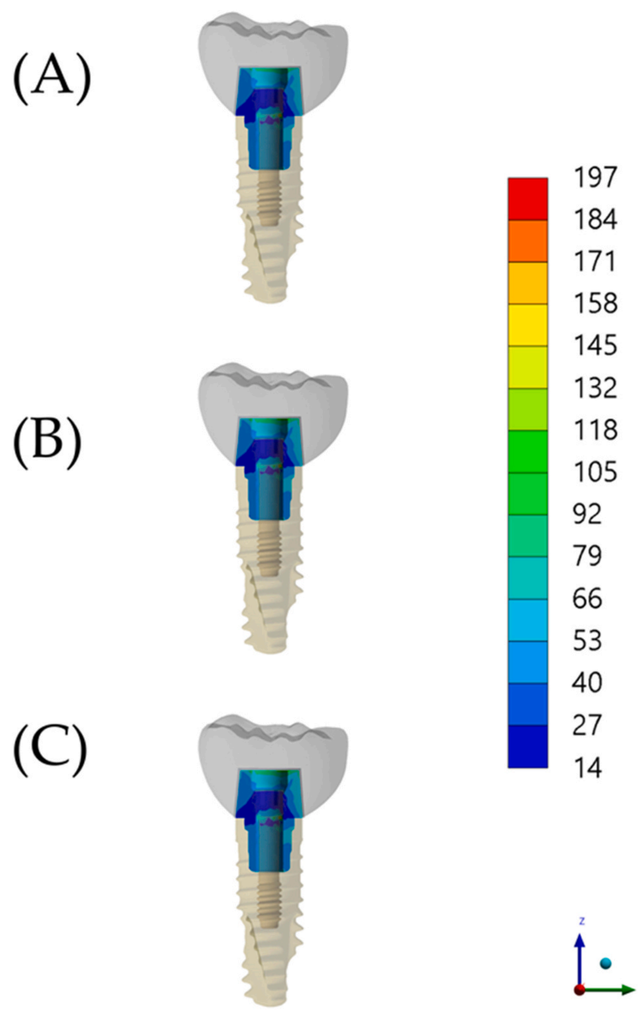

Fig. 10 – Section plane for von-Mises Stress contour plots for the abutment according to the different crown materials. A) Estelite Block II, B) Estelite P Block and C) Estelite Layered Block.

CAD CAM composite blocks [27]. The use of nanohybrid filler technology and modified resin matrix composition in the nano-ceramic hybrid resin composite CAD/CAM blocks improved most of its physico-mechanical properties, resulting in reduced elastic moduli as well as high flexural strength.

At one time, gaps between particles and the resin matrix were difficult to eliminate, but now nanofillers can be added and bind tightly by polymerization. However, increasing the size of filler particles makes it problematic to reduce microgaps at the interfaces between the filler and resin matrix. This may result in a partial break of the resin and filler coupling reducing material strength [24]. Therefore, as a limitation of this study, fatigue was not simulated and the effect of microcrack formation between matrix and fillers was not evaluated.

A previous study reported that stable esthetic resin-based CAD/CAM restorations play an important role throughout their functional lifetimes. A good color match and translucency of a restoration are as important as the mechanical properties of the reinforced hybrid composite block [24]. The present study corroborates that, indicating that all evaluated CAD/CAM blocks could be indicated for posterior crowns with acceptable mechanical response.

Similar to the present investigation, a previous finite element study aimed to evaluate the mechanical behavior of an implant-supported crown made using resin composite in the posterior region [10]. The authors simulated four commercially available CAD-CAM resin-based blocks from different manufacturers. They concluded that implant-supported crowns fabricated with four different CAD-CAM showed no

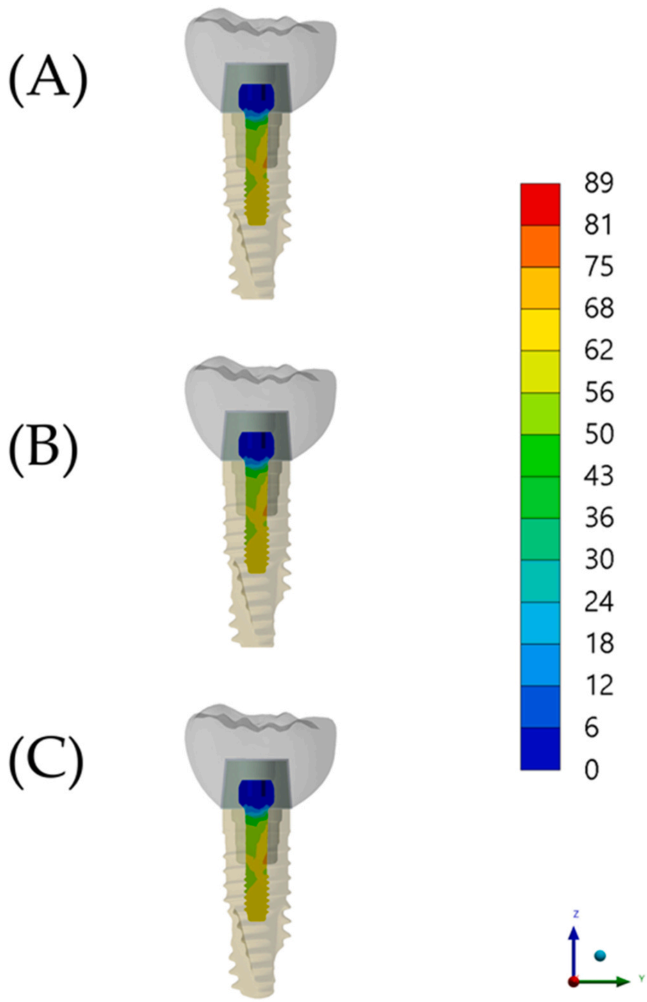

Fig. 11 – Section plane for von-Mises Stress contour plots for the prosthetic screw according to the different crown materials. A) Estelite Block II, B) Estelite P Block and C) Estelite Layered Block.

Table 2 – Stress peak for each model evaluated according to the region of interest and restorative material.

Model	Region	Stress (MPa)
Estelite Block II	Crown	18.08
Estelite P Block		19.23
Estelite Layered Block		17.53
Estelite Block II	Implant	197.36
Estelite P Block		197.33
Estelite Layered Block		197.35
Estelite Block II	Screw	88.18
Estelite P Block		88.14
Estelite Layered Block		88.17
Estelite Block II	Abutment	127.49
Estelite P Block		127.51
Estelite Layered Block		127.49
Estelite Block II	Cement Tensile	32.43
Estelite P Block		19.64
Estelite Layered Block		31.48
Estelite Block II	Cement Shear	33.26
Estelite P Block		22.12
Estelite Layered Block		33.57

critical stress concentrations in the bone or implant suggesting that they could be used as an alternative material for implant-supported restorations in the posterior region in terms of stress distribution [10]. This study corroborates those findings, showing a reduced amount of stress in the implant, abutment, screw and bone tissue. In addition, we evaluated stress in the resin cement layer, something that was not previously simulated.

A previous literature review investigated the influence of the prosthetic restorative material on the stresses in bone tissue and peri-implant via three-dimensional finite element studies. Most of the articles indicated that the prosthetic material does *not* influence the generation of stress and dissipation in the bone and peri-implant tissue [28]. The authors reported that monolithic crowns usually show a decrease in stress concentration, as the stresses were more present on the crown surface due to its elastic modulus, which consequently reduced the load transmission to the implant and the bone [28]. The present results agree with that, showing that the effect of crown material was limited to the crown itself as well as the cement layer. All other structure below them, were not affected by variation in the crown elastic modulus.

The present model is limited to unitary crowns. For tooth-supported CAD/CAM fixed partial dentures, the use of resin composite as a restorative material reduced the stress concentration in the cement layer, suggesting a beneficial response in the adhesive interface in comparison with other polymeric materials [22,29]. However, there is lack of this type of FE data for implant-supported fixed dental prostheses and further studies should be developed to assess that topic.

An in-vitro study investigated the effect of cyclic loading fatigue and different luting agents under wet conditions on the fracture load of CAD/CAM resin-based and all-ceramic crowns. According to their findings, cyclic loading fatigue significantly reduced the fracture loads of resin composite and all-ceramic crowns, whereas adhesive luting procedures significantly increased the fracture loads [30]. Therefore, it seems that, despite the advantages of resin-based crowns, cyclic fatigue can still cause deleterious effects.

Focusing on resin-based restorations, another investigation aimed to ascertain whether CAD/CAM resin composite crowns mechanical behavior. It was found that resin composite crowns had about 3–4 times higher fracture load than the average maximum bite force, suggesting that CAD/CAM resin composite crowns would have sufficient strength to withstand the bite force from molar teeth [31]. This is in agreement with the present investigation, that showed failure risks less than 10 % for all evaluated materials when 600 N of force was simulated.

Fig. 12 – Failure risk for the crown according to each material mechanical property and stress peak.

A previous laboratory study showed that monolithic implant-supported crowns had higher initial-fracture loads than conventional veneered ceramic crowns. In addition, they found that monolithic ceramic restorations might perform better than resin composite crowns [32]. Via finite element analysis they showed that crowns with a fixed connection between the abutment and crown shows a maximum stress at the interface crown/abutment in the cervical region that exceeded the cement bond strength. This statement is consistent with the present investigation, as demonstrated by stress peaks summarized in Table 2.

The present study is a theoretical analysis to evaluate the biomechanical behavior of materials. However, there are inherent limitations that should be clarified by further data prior to definitive clinical recommendations [4,6,11]. The absence of variables such as pH changes [12,13], biofilm, temperature and the use of isotropic materials are some of the major limitations. The finite element method can identify regions under stress and regions of possible failures according to the geometry and mechanical behavior of dental materials [20–23]. However, fatigue lifetimes (S-N curves) should be determined for restorative materials, to provide a more complete in vitro evaluation.

5. Conclusions

For the analyzed material combinations the FEA linear analysis, assuming isotropic elastic material behavior, suggests that these resin-based CAD/CAM materials showed promising mechanical responses as implant supported crowns. Stress and strain distributions and failure risk ratios indicated that they may be considered as a good option for the fabrication of CAD/CAM indirect dental restorations.

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