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Campus de São José dos Campos

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UNESP UNIVERSIDADE ESTADUAL PAULISTA "JÚLIO DE MESQUITA FILHO"
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Biomechanics of implant-supported restorations

Biomecânica das restaurações implantossuportadas

Guilherme Schmitt de ANDRADE[1], **Les KALMAN**[2], **Roberto LO GIUDICE**[3], **Dario ADOLFI**[4], **Albert J. FEILZER**[5], **João Paulo Mendes TRIBST**[5]

1 - Western Paraná State University, Center for Biological and Health Sciences, Department of Dentistry, Cascavel, PR, Brazil.
2 - Western University, Schulich School of Medicine and Dentistry, London, ON, Canada.
3 - Messina University, Department of Clinical and Experimental Medicine, Messina, Italy.
4 - São Paulo State University, Institute of Science and Technology, Department of Dental Materials and Prosthodontics, São José dos Campos, SP, Brazil.
5 - Universiteit van Amsterdam and Vrije Universiteit Amsterdam, Academic Centre for Dentistry Amsterdam, Department of Oral Regenerative Medicine, Amsterdam, The Netherlands.

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ABSTRACT

The rehabilitation of patients with dental implant-supported restorations is an ideal treatment option in contemporary dentistry. The aim of this review was to compile and to demonstrate the mechanical response during loading condition, on the stress distributions of implant-supported prostheses. The findings show that the majority of stresses were concentrated in the cervical region of the implant/abutment interface and that they can be affected by several clinical parameters and loading conditions. Finally, the final prosthetic design should combine superior mechanical response, long-term survival rate and allow patient satisfaction.

KEYWORDS

Prostheses and Implants; Dental Implants; Finite element analysis; Review; Biomechanics.

RESUMO

A reabilitação de pacientes com restaurações implanto-suportadas é uma opção de tratamento ideal na odontologia contemporânea. O objetivo desta revisão foi compilar e demonstrar a resposta mecânica durante a aplicação de carga, na distribuição de tensão de próteses implanto-suportadas. Os achados mostram que a maioria das tensões se concentram na região cervical da interface implante/pilar e pode ser afetada por diversos parâmetros clínicos e condições de carregamento. Por fim, o desenho protético final deve combinar uma melhor resposta mecânica, taxa de sobrevida a longo prazo e permitir a satisfação do paciente.

PALAVRAS-CHAVE

Próteses e Implantes; Implantes dentários; Análise por elementos finitos; Revisão; Biomecânica.

INTRODUCTION

Based on a didactic and general explanation, the term "biomechanics" can be defined as mechanics applied to biology, while mechanics is derived from the response of the structure to forces or displacements [1-3]. Biomechanical principles in implant dentistry remain as crucial as the clinical parameters that must be applied for oral rehabilitation. Ignoring or not applying the principles will ultimately lead to clinical failure [1]. These principles can be identified during prototype development, production and testing of implant-supported restorations and during all clinical stages, including planning, insertion, loading and maintenance [1].

The control of the clinical parameters plays an important role in the implant therapy, since the interactions between the soft and hard biological tissues and synthetic structures (and in association with external forces) generates a mechanical response proportional to the applied load. With endosseous implants, the load that acts on the dental implant are transferred to the surrounding peri-implant tissues and may be modified from different factors [4].

Throughout the treatment plan phase, it is mandatory to consider how these forces, which will be applied to the dental implant, may be generated in terms of: type, direction, magnitude, duration and physiology [1-6]. According to the literature, the 5-year survival rates range from 97.1% - 100% for fixed prostheses and 95% - 100% for removable prostheses that are implant supported. However, in the daily practice, high survival rates are not the only factor to define the success of implant treatments, as it only represents those prostheses remaining in use during the follow-up period. These indices do not indicate whether or not these prostheses were affected by mechanical complications, which may influence the general success of the implant treatment [5]. A lack of understanding of mechanical principles during the placement of implants may lead to increased complication rates, repairs, remakes, inefficiencies and increased cost; which may ultimately affect the patient's life quality [6].

The challenge of standardizing dental implant biomechanics includes the continuous evolution in biomaterials, implant designs, no consensus on technical procedures and lack of control of factors that can increase the stress magnitude. Understanding and aiming for a more biomimetic implant-supported prostheses can facilitate the design of a more reliable restoration, with reduced mechanical complications in a long-term follow-up.

In many cases, mechanical complications can lead to implant fracture, as any object subjected to constant loading may undergo overload conditions and subsequent failure, resulting in a clinical complication [4]. A common dental condition, parafunction, can result in the production of extreme forces. Prolonged period of parafunctional forces may surpass the endurance limit of the biomaterials, leading to problems such as screw loosening, fatigue failure, prosthesis fracture and even unwanted bone remodeling around the implant [4]. The most common mechanical-related complications in implant dentistry are: (1) fracture or loosening of retaining abutment/prosthetic screws (2) loss of crown retention and (3) chipping or fracture of the veneered material [7].

The aim of this study is to review and to illustrate, with stress maps, the various clinical parameters previously reported in the literature as significant influences on the biomechanics of implant-supported restorations. Please note that chemical and biological factors have not been included in this study, but they also play an important role in the biomechanics.

BACKGROUND

There are some critical fundamental concepts and principles of biomechanics that must be appreciated to understand how they affect the success of implant-supported restorations.

MOMENT ARMS

In a didactic division, six rotational moments can be found according to the three clinical coordinate axes in an implant-supported restoration (faciolingual, mesiodistal and vertical axes). Due to the chewing load, micromovements would present higher amplitude and higher stress magnitude when aligned with any of the rotational moments [7,8] (Figure 1).

Reducing the effect of these moment arms is essential to decrease the restorations' chances of failure [7-9]. And a balance between the ideal load distribution and the patients' needs should guide the final planned design for each case. Nevertheless, the understanding of moment arms is essential to plan predictable and successful cases.

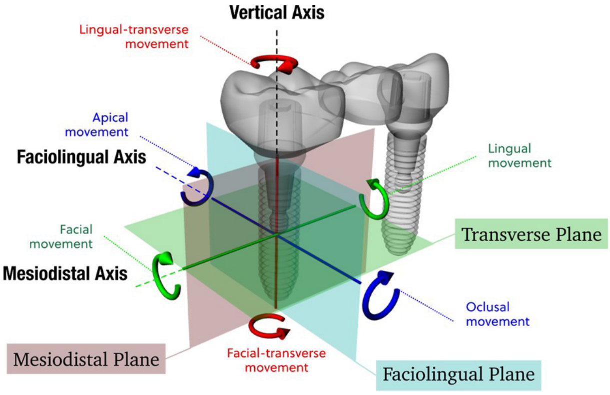

Figure 1 - Three-dimensional moment arms according to the clinical coordinate axes in implant-supported restorations.

IMPLANT QUANTITY

One of the first parameters that should be observed in a patient case, prior to prosthetic planning, is the available support for the missing teeth. This parameter will dictate how the prostheses can be supported. Previous investigations have assessed the effect of the number of implants to be used in implant-supported prostheses [9]. Therefore, during the treatment planning, the number of implants required to support the prosthesis is one of the most important factors to be considered, since this step cannot be easily modified without a new surgical intervention [8]. The literature indicates that stresses are inversely proportional to the number of implants; due to the fact that the load can be distributed accordingly to the quantity of endosseous implants in the arch. The mechanical response usually demonstrates a consistent relationship between the implant number and the calculated strain around the bone tissue [9-11].

Although there is no consensus regarding the quantity of implants required for an ideal stress distribution and minimal bone microstrain, an increase in implant number is suggested as beneficial, corresponding to a more predictable approach for the patient rehabilitation [11]. Therefore, it is important to consider how the load will be distributed between the implants, if the amount of endosseous implants are suitable to support and to retain the planned prosthesis, or if the treatment must be delayed or modified. For example, in clinical situations with only two implants have been placed between the mental foramen, the patient can properly receive a removable overdenture, while a fixed prosthesis would increase the treatment's failure risk [12]. However, in both conditions, the final prosthesis would still be able to rehabilitate the patient, with the same number of artificial teeth. Although, the implant retained option would improve the quality of life of the patient.

Figure 2 illustrates the rehabilitation of a patient with the same number of missing teeth. However, using only two implants to support a three-unit prosthesis leads to more stress in the abutment, as well as, in the connector region of the bridge.

IMPLANT POSITIONING

A restorable implant is a critical requirement for planning oral rehabilitation as well as the osseointegrated implant needs a proper abutment to support the prosthesis. Therefore, another fixed parameter is the implant positioning. The prosthesis cannot modify the position of the implant in the bone after osseointegration.

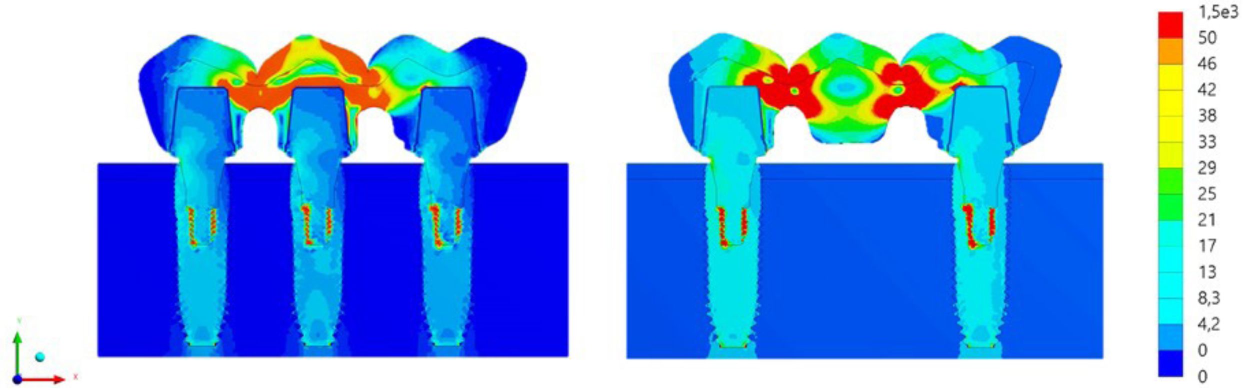

Figure 2 - Stress maps showing a 3-unit fixed dental bridge supported by three or two-implants with the incidence of 100 N of loading. The use of more implants reduced the stress magnitude at the connector and dissipate more stress to the central abutment

However, the prosthetic design can correct the insertion path and aesthetics, even in a non-ideal condition. With the advent of angulated screw channel abutments, it has allowed potential cement-retained restorations to be converted to screw-retained restorations. In these cases, it is possible to use angulated screw channel abutments to change the angle at the abutment or at the soft tissue level. This allows the opportunity to place angled implants, which can then be compensated with angled screw channel abutments [13].

According to an *in vitro* investigation, the implant angulation did not affect the digital impression accuracy. However, due to the lack of supporting evidence, the extrapolation of this statement for inclined implants for every condition is not indicated [14]. Additionally, errors in the impression method could generate inaccurate models and consequently, misfitted prostheses.

Despite the preference of axial loads on implant-supported restorations, this condition cannot always be achieved in all cases. Situations such as pneumatization of the maxillary sinus and bone atrophies are obstacles to the ideal implant placement that may sometimes require regenerative therapies, such as bone grafts. Therefore, depending on the bone availability and the patient-specific anatomy, the implant may be placed in a no-ideal position [14-17] and consequently will receive oblique loads.

In addition to the surgical plan, different regenerative therapies such as the split-bone block technique and the cortico-cancellous block graft, exhibit different healing processes which may influence bone incorporation and resorption [15]. After the healing process, any modification in the bone dimensions can compromise the ideal placement of the implant fixture, since the bone morphology may also guide de implant position [16].

In summary, patient's rehabilitation with inclined implants will require more frequent monitoring and control of forces, as a previous finite element analysis (FEA) demonstrated that improperly positioned implants result in the highest stresses for all prosthetic components [17]. Additionally, failure at the screw-joint interface can also be associated with the presence of inclined implants. With the presence of oblique loads, high stress is projected in the prosthesis and in the bone. Consequently, the maximum fracture load of the components is lower, increasing the chance of mechanical failure during function [18].

CANTILEVER SPAN

After restoration placement, its durability is a critical factor for clinical success, since mechanical failures, in the form of fractures, have economic consequences for both patient and dentist. This can be of particularly concern when considering cantilever structures, replacing more teeth than the amount of available abutments. Cantilever prostheses represent a projecting structure that is supported at only one end by the abutment. This situation may arise when it is not possible to place another implant, due to anatomical features, limited finances or any other reason. The prosthetic structure must be able to withstand the function and dissipate the forces through its structure, implants and bone, without visible elastic or plastic deformation [19,20].

Different reports have indicated that the clinician should plan the implant-supported rehabilitation to promote an axially force transmission through the prosthetic structures [20,21]. This recommendation is crucial since a chewing load with equal intensity, applied at different sites of the prosthetic structure, can significantly modify the mechanical behavior of the implant and the bone. Based on this, careful attention is needed when planning cantilevered implant-supported rehabilitation, since the treatment plan inherently incorporates a compromised axial load transmission (in the function of the presence of a horizontal lever arm) [21]. Figure 3 illustrates a posterior fixed dental prosthesis in which the number of prosthetic abutments is higher than the number of cantilever elements, aiming to reduce the effect of the cantilever.

To avoid possible damage caused by an extremely extended lever arm, the final dimension of the arm should be well controlled and properly designed by the dentist and the dental technician. This recommendation is significant since the cantilever increases the power arm of the horizontal lever, and its magnitude should also be evaluated according to the fixed part of the lever, i.e. the resistance arm [22]. Therefore, the cantilever length should be measured from the center of the last implant platform until the region of load application [23]. In addition, the cantilever is more commonly extended to distal side which tends to be more detrimental; however, it can also be extended to the mesial as presented in the Figure 3.

It is plausible that the impact of the cantilever bending with anterior implants would be more destructive in cases with unfavorable arch geometry, an excessive overjet, and with inclined implants [22]. However, for posterior implants, the amount of stress magnitude would be proportional to the cantilever length. The first option to reduce any undesired biomechanical effect caused by a cantilever arm is simple: reduce its extension or length. A reduced cantilever arm can generate less stress magnitude around the last implant, modifying the power arm in a positive ratio (Figure 4). However, in a short-span cantilever, fewer teeth can be placed in the prosthetic design, sometimes requiring smaller dental elements or modified occlusions concepts (e.g. reduced occlusal platform) to properly rehabilitate the arch.

Another option to reduce the cantilever length is using a higher inclination for the implant's placement, an approach that can also improve the mechanical response with lower stress magnitude in full-arch-rehabilitations [22]. However, this option could only be possible if the surgical phase was planned accordingly. In addition, inclined implants with the same cantilever length as axial implants can negatively impact the biomechanical behavior and compromise the treatment longevity [21-23].

SPLINTED CROWNS

The conventional hypothesis for splinting implant-supported crowns is to decrease stresses and improve prostheses stability. This hypothesis inspired several investigations in the sphere of biomechanics in dentistry.

A previous photoelastic investigation of a partially edentulous mandible observed that the effect of splinting crowns, on the strain transference to implant-supported restorations, was that they shared the occlusal loads and distributed the strain more homogeneously between the implants [24].

Another *in vitro* study evaluated the effects of two types of superstructures (splinted and non-splinted crowns) on four vibration

Figure 3 - Rehabilitation with a four-unit posterior bridge of the first premolar using a mesial cantilever concept.

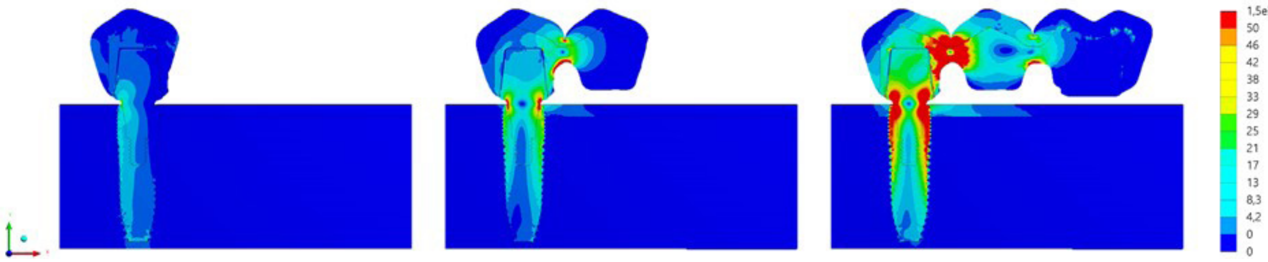

Figure 4 - Stress maps showing a posterior rehabilitation with different cantilever lengths and the incidence of 100 N load. It is illustrated that the higher the lever arm, the higher is the stress concentration.

characteristics (natural frequency, damping ratio, vectors in antiphase and maximum displacement) by using modal analysis. According to their findings, the crown splinting reduced the deformation of the superstructure, the implants, and the surrounding tissues, in comparison to the deformation observed when no splinting was employed [25]. The mechanical behavior reported in these *in vitro* investigations corroborates the findings from the stress theory. Using a FEA, the stress distribution in the implants, components and the bone tissue for splinted and non-splinted crowns were evaluated with different lengths of implants. The authors demonstrated that the design with splinted crowns promoted lower stress magnitude in evaluated structures [26].

To date, there is no consensus in the scientific literature about the ideal prosthetic design that should be used to optimally restore multiple implants in the posterior edentulous region, to reduce strain during loading. However, it seems plausible that splinted prosthetic designs present a suitable biomechanical behavior when compared with a fixed bridge [27]. Figure 5 shows the strain maps for the cortical bone with non-splinted and splinted crowns. Based on this image, the use of splinted crowns appears to be more beneficial for the central implant.

CROWN/IMPLANT RATIO

Among the biomechanical parameters that can be cited, the crown-to-implant ratio has been extensively investigated in biomechanical studies and theoretical analyses. It can be generally defined as the relationship between the crown height and the implant lengths. The common condition on this concept is related with the use of short implants, since their use frequently results in prosthetic rehabilitations with high crowns length and unfortunately, the creation of a deleterious fulcrum [28]. A systematic review investigated the effect of the crown-implant ratio on the survival rate and complication incidence of implant-supported prostheses. According to the authors, the collected information was insufficient to analyze the relationship between the crown-implant ratio and technical complications in implant-supported prostheses [29].

In theory, the crown-implant ratio can impact the bone level maintenance. According to previous studies, lower crown-implant ratio may induce lower stress magnitude on the implant-supported prostheses; thus, reducing technical complications in the components [30,31].

In vitro strain gauge and photoelastic analyses have demonstrated that different crown-implant ratios presented no significant differences in buccal or palatal microstrain when the force was applied through the long vertical axis of the implants [31,32]. However, the prosthetic crowns are not exclusively submitted to axial loading. A numerical simulation evaluated the stress distribution in the fixation screw and bone tissue around internal hexagon implants in single-implant supported prostheses with crowns of different heights. According to the investigation, the increase of the prosthetic crown height induced higher stress concentrations in the fixation screw and in the bone tissue around implants, under oblique load [32].

It was recommended that the occlusal design should be carefully planned, since factors such as a non-axial load, bruxism, bone quality and systemic conditions, might induce loosing and/or fracture of the fixation screw, as well as, the initiation of progressive bone loss [32].

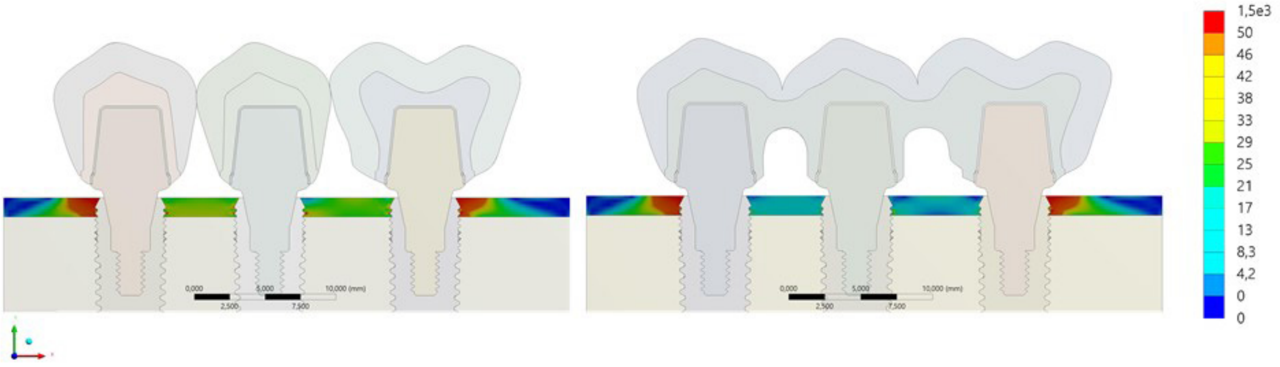

Figure 5 - Strain in cortical bone with a 3-unit prosthesis with individual crowns or with splinted crowns (a bridge) after the incidence of a 100 N load on each tooth. Higher strain at the central implant is visible when the crowns are not splinted.

Nevertheless, short implants may be considered as an alternative to standard implants, due to their simplicity and lower-cost, since they can be placed in different areas to avoid sinus lifts and nerve repositioning. Another application may be to shorten the treatment time in patients that require faster treatments [33]. However, further research in this field is required due to the lack of data regarding the success and failure in comparison with standard implants.

Figure 6 illustrates the stress generated in an implant-supported crown at different heights when an oblique load is applied. It is illustrated that the area more prone to failure is in the implant-abutment joint and the prosthetic screw.

LOADING DIRECTION

In vivo and *in vitro* studies have illustrated the potential detrimental effect of excessive mechanical load on peri-implant bone. Clinically, certain factors are able to increase the load effect and the incidence of no-axial loads. This is supported by previous investigations on early and immediate implant loading, which provided information on the impact of mechanical loading on the process of osseointegration. It was demonstrated that micromotion between the implant and peri-implant tissues compromises the osseointegration process [34].

Corroborating with previous investigations with FEA, histological and Immunohistochemistry analyses, it was to demonstrated that traumatic occlusion resulted in changes in alveolar bone mechanobiology morphology [35]. It is common in the implant dentistry to evaluate stress maps generated during loading, to indicate that the stress concentration is particularly high at the bone–implant interface in different locations: distal, medial and proximal zones. In addition, the distribution and the magnitude of the equivalent stress induced in the dental prosthesis depends on the nature of the functional loading [36]. Figure 7 illustrates how the same posterior crown can have different mechanical responses by modifying the incidence of the load direction. Note that the amount of force remains the same, i.e., the patient is not biting harder.

Variations in macro and micro implant design can modify the implants mechanical response, as well as, their role in the bone tissue mechanical response, during compressive loading. Despite the effect of several factors, which have been previously explored in the literature, investigations demonstrated that each clinical case presents unique combination of parameters that are still necessary to be evaluated to provide useful information for clinical practice [37]. In most of the cases, excessive loads are concentrated around the cervical region, causing microcracks in the bone, resulting in implant loosening and eventual failure. This tendency became more pronounced with a 45° loading direction and eccentric loading [38]. Based on this mechanical behavior, it was reported that axial loads are less harmful to the bone tissue, as the stresses are distributed throughout the implant, while oblique loads tend to create higher bone microstrain in the bone tissue [39].

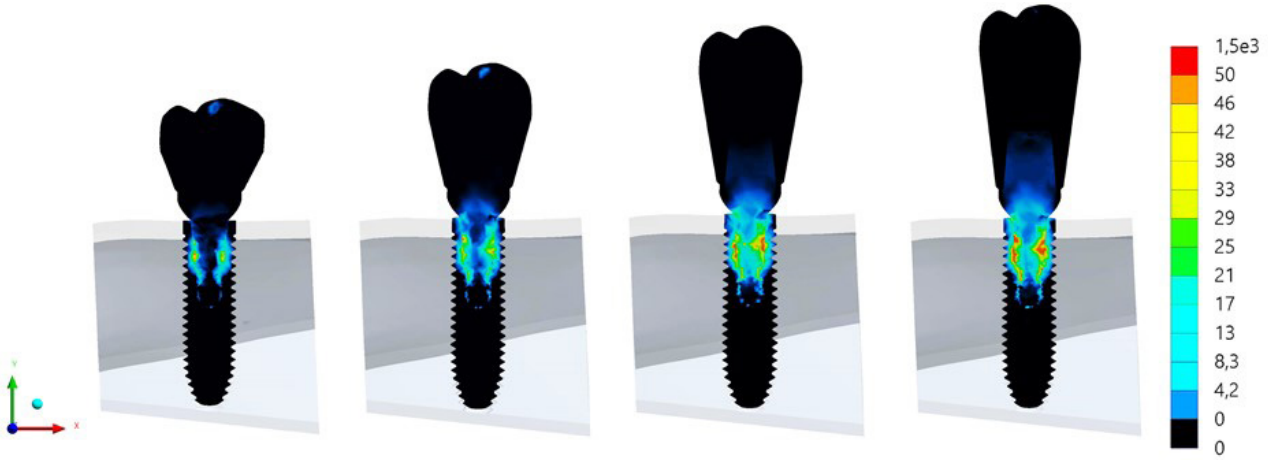

Figure 6 - Stress at the unitary posterior crown with different heights after the incidence of 100 N (45°). The stress level increases proportionally to the height of the crown.

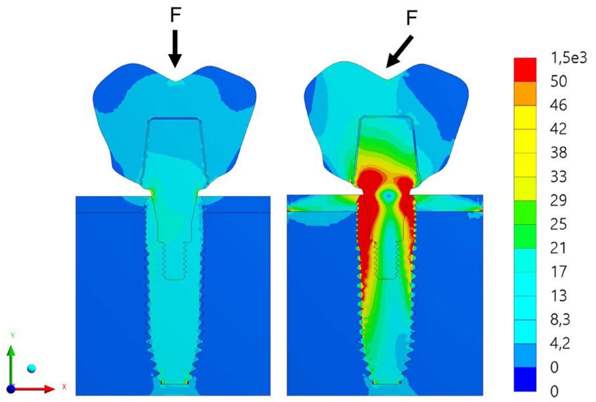

Figure 7 - Stress at the unitary posterior crown after the incidence of 100 N axially to the implant axis and oblique to it (45°).

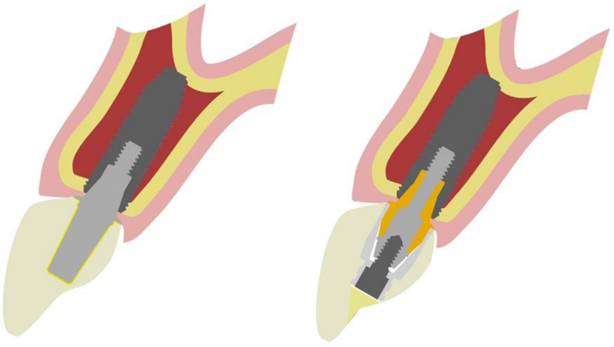

Figure 8 - Schematic illustration showing an anterior cement-retained and screw-retained crowns for the same case.

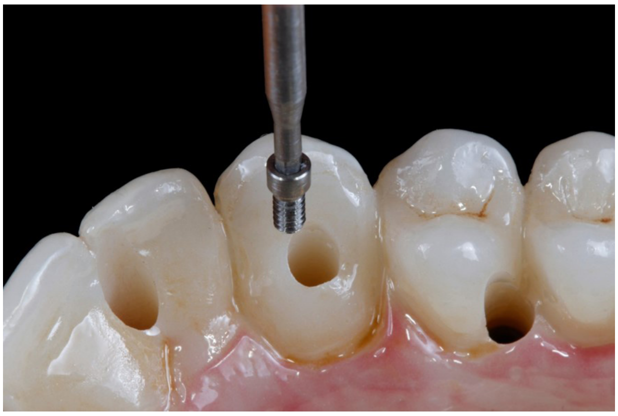

Figure 9 - The reversibility of screw-retained restorations is an important advantage of this design, although the aesthetics can be slightly impaired with the screw-access hole.

It was also suggested that the distribution of forces can mitigate implant overload, through multiple occlusal contacts on multiple posterior teeth, instead of a single contact in just one crown. However, multiple contacts placed away from the center of the implant can cause a cantilever effect, modifying the load incidence from purely axial to an oblique vector [40]. In summary, occlusal contacts that occur away from the implant's axis generate greater implant and peri-implant stresses and had a greater effect on resultant stresses than increased cusp inclination. This mechanical behavior can be observed during a bending movement at the implant-bone interface, as the implant lacks an initial adaptive phase of movement, as opposed to a natural tooth with absorption of forces by the periodontal ligament [40].

Furthermore, an occlusal anatomy design with reduced cusp angulation and less evident occlusal sulcus, can reduce the stress concentration and increase the fracture load for ceramic posterior crowns. Therefore, less pronounced occlusal anatomy would improve implant loading distribution and could be beneficial for the survival of the restoration [41-43].

CROWN-RETENTION SYSTEM

Another parameter that the clinician can control is the crown-retention system (Figure 8). The crown-retention system is usually divided into cement or screw-retained [44-49]. There is no consensus regarding the most appropriate retention type for long-term implant survival, since the clinician's experience tends to be the most important factor when selecting the type of retention used in implant rehabilitations [43,45].

Notwithstanding, there are unique considerations for each type of retention. The screw-retained restoration can be easily removed when maintenance is required; however, the screw-access hole can negatively impact the final esthetics [46-49]. In addition, the screw-access hole must be closed with resin composite, which can suffer wear or debonding (Figure 9), compromising the occlusal anatomy [47]. The cement-retained restoration can improve the crown esthetics and the final retention will be related to the abutment dimension [49]. Moreover, excess of residual cement can promote inflammatory process in the surrounding tissues, which is a harmful condition for the oral health [43,44].

The mechanical stability of the prosthetic components in the implant-prosthesis complex is essential to the long-term success of the restorations. However, little is known about the differences in the biomechanical behavior of screw or cement retained prostheses. According to a previous study that compared the pre-load maintenance, stresses, and displacements of prosthetic components of screw and cement retained implant-supported crowns, the screw-retained prosthesis demonstrated a higher risk of screw loosening and fracture [42]. However, other study compared the stresses and displacements in the peri-implant bone generated by screw and cement retained prostheses using the FEA. Results illustrated a similar pattern in the distribution of the principal stresses between both prostheses [46]. The lack of consensus in the literature is reflected by variations in the design of the prosthesis. The retention of implant restorations can be impacted by other factors, such the cantilever length and the loading direction of implant positioning. However, as a generality for the implant and bone tissue, the difference between both retention systems would be insignificant in stresses, when similar biomaterials and abutment dimensions are compared (Figures 10 and 11).

A previous systematic review of 39 studies aimed to assess the technical and biological complications of screw and cement retained implant-supported full-arch dental prostheses, found that cemented retained restorations exhibited more biological complications, and that screw-retained prostheses exhibited more technical problems [50]. Clinical outcomes were affected by both systems in different ways. The screw-retained restorations were more easily retrievable than cemented ones, implying that technical and eventually biological complications could be prevented and/or treated more predictably. Based on the easier retrievability and higher biological compatibility, the authors suggest that screw-retained restorations are preferable [50].

PROSTHETIC CONNECTION

As previously mentioned, the crown can be retained by either cement or using a screw. The abutment, which can exist as two-pieces,

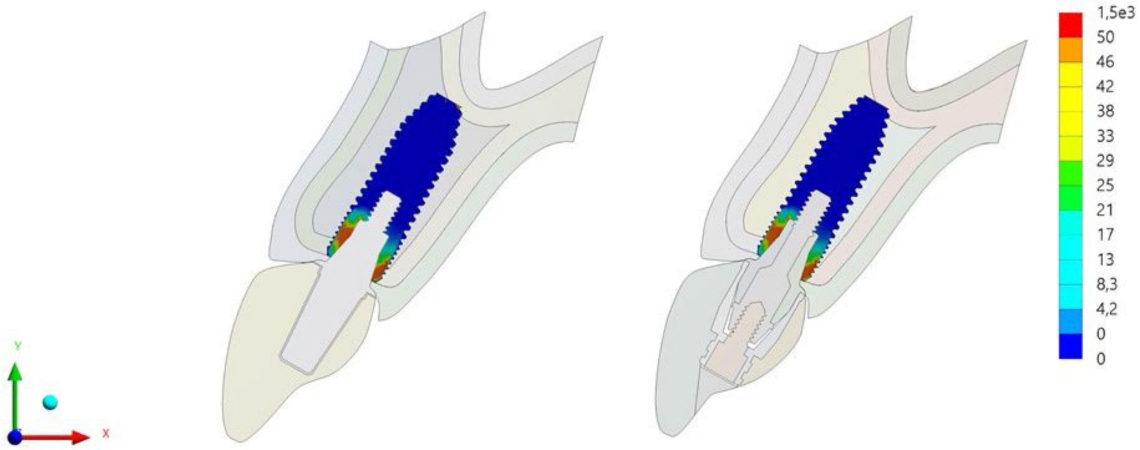

Figure 10 - After similar loading (100 N), there is no difference in the generated stress maps according to the crown-retention system.

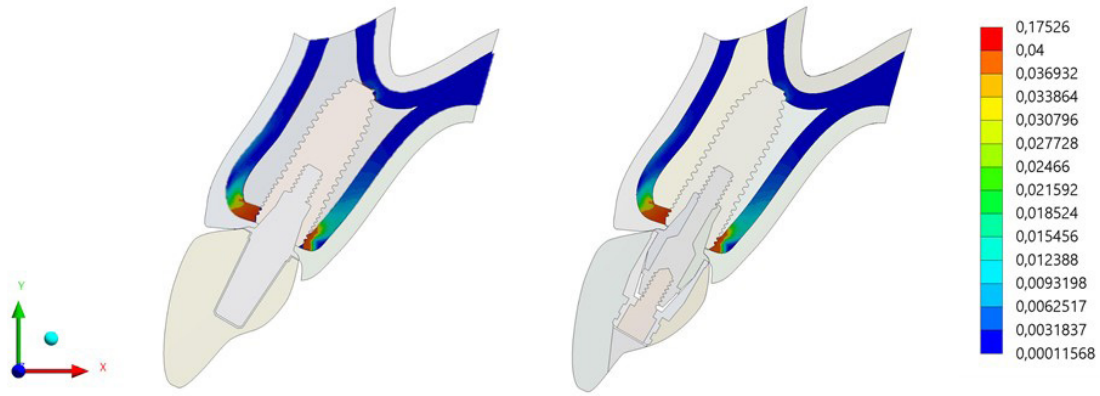

Figure 11 - After similar loading (100 N), there is no difference for the strain maps generated with both crown-retention system for the cortical bone strain.

are usually retained by a screw and connected with the implant with its prosthetic connection (Figure 12).

According to a report, the implant connection type had a greater impact compared to the diameter on the stress in the implant and abutment. When selecting the dental implant type, the connection type should be considered as an important factor, as well as, the size of the restoration [51]. There are several type and designs of connections; however, the most common are the external hexagon, internal hexagon and the Morse-taper.

Connection types were also assessed with three-dimensional FEA. The preceding investigation evaluated the mechanical influences of the implant–abutment connection type and inter-implant distance on the bone stress. Using computer-aided design models of implants with external connection, internal connection and conical connection, a previous investigation demonstrated that the stress of the inter-implant bone increased as the inter-implant distance decreased [52]. Comparing only internal connections, systems that contained a retention screw had the disadvantage of concentrated stress, while a solid abutment retained by friction dissipates the load through the implant and suggests improved performance [53]. However, the frictional abutment is not available for every system and is not always easily removed when required [54].

A previous report demonstrated that the abutment connection also affects the stress concentration in peri-implant bone [53-55]. However, the authors considered the effect of platform switching as a factor between models with a similar Morse taper connection [55]. Comparing external hexagon and Morse-taper designs, a numerical simulation with strain gauge validation indicated no difference regarding the prosthetic connection for the generated stress and strain under axial load. The authors concluded that both implant connections exhibit similar biomechanical behavior regardless of the bone height [39]. However, another 3D-FEA illustrated a different mechanical behavior on the prosthetic screws between external hexagon implants and Morse taper implants, when different tightening loads were present. According to their findings, the torque loads above the manufacturer recommendations can cause plastic deformation in the Morse-taper abutment screw threads. The screws of Morse taper implants can be more sensitive to higher loads than external hexagon implants [55].

EMERGENCE PROFILE

The emergence profile ideally should be designed following the soft tissue, to improve the natural aesthetical look of the implant-supported crown. However, to increase the amount of peri-implant tissue, it is necessary to reduce the volume of restorative material at the cervical level (Figure 13). This concave silhouette approach increases the biological benefits for soft tissue stability, such as marginal sealing, blood supply and stable bone level. It is important to understand that the cervical area is highly prone to fail since fractures can occur in this area due to high levels of stress magnitude [56].

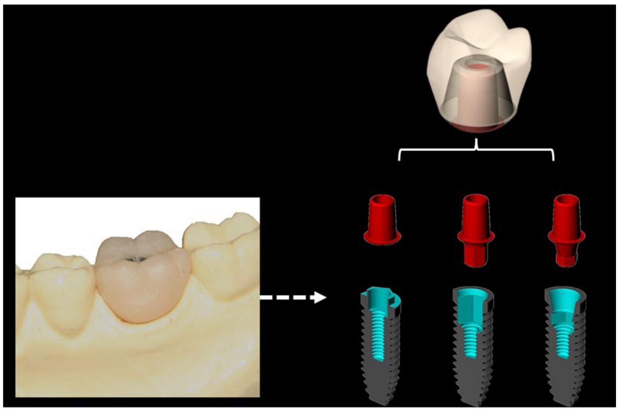

Figure 12 - An implant-supported crown can be retained by different implant connections that share the same clinical indication.

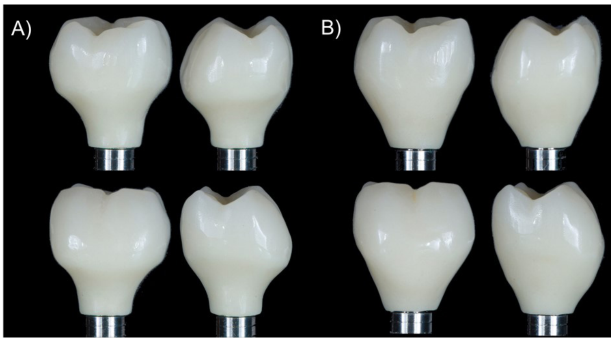

Figure 13 - Zirconia monolithic crown with different emergence profile concepts. (A) After the proper soft tissue conditioning and (B) with more ceramic volume. In this case, the CAD anatomy used for both crowns designing was similar in the software and only the emergence profile was modified.

Stress concentrations associated with fractographic analysis suggest that the emergence profile of the restoration should always be evaluated, due to the high prevalence of failures in this area [56]. The reduced amount of restorative material in the cervical level is a desirable feature in contemporary crowns design, since the proper emergence profile improves esthetic outcomes and provides favorable biological response to implant-supported restorations [57]. With the aid of CAD/CAM technology, it is possible to design the natural emergence profile for posterior implant crowns, ensuring a more predictable and efficient restoration for optimal oral hygiene. However, the keratinized tissue, with sufficient width and height, needs an abutment with large diameter to ensure stability and esthetics of hard and soft tissues around the implants [58].

In some cases of atrophic maxillary bones, implant placement can be a challenge [59], and this may also impair the design of the prosthesis. It is not uncommon that recession of the peri-implant soft tissue margin may occur after crown placement, increasing the risk of exposition of the implants threads [60]. A modification with the implant/crown ratio and the limitations of short implants, in relation to occlusal forces, can result in torque loss and reduced survival rate. To compensate this, the height of the abutments should be selected with longer collars [33].

Figure 14 illustrates two molar crowns with and without an adequate emergence profile. When less restorative material is used, the amount of force required to fracture the crown is also reduced. Therefore, it is critical to assess the cervical thickness of ceramic crowns to maximize predictability and success of implant-supported crowns.

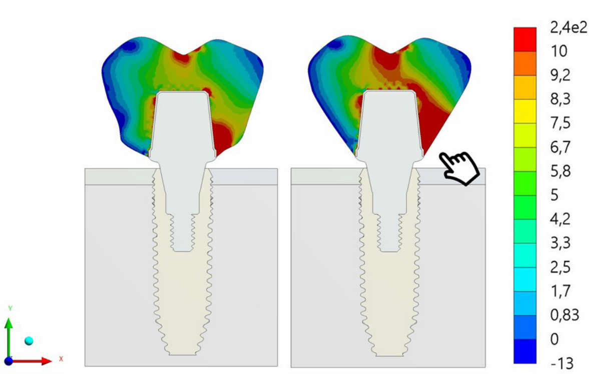

Figure 14 - Stress at the unitary posterior crowns after the incidence of 100 N oblique load (45°) to the implant axis. The crown with adequate emergence profile demonstrates higher stress magnitude due to the reduced volume of restorative material.

OCCLUSAL SPLINT

After considering all previously mentioned factors that can affect implant-supported restorations' success and longevity, it is imperative to limit occlusal loads. A promising way to protect implant-supported restorations is with the recommendation and utilization of an occlusal splint appliance. It was demonstrated that the occlusal appliance can modify the contact distribution on occlusal surfaces, changing the stress distribution and displacement patterns in implant-supported bridges [61].

With the use of an occlusal appliance, the lowest possible stress levels at the abutment and implant, and the most favorable stress distribution, between the cortical and trabecular bone, can be achieved [61]. Observing the stress maps calculated in a prior study, under parafunctional loading, an occlusal appliance was effective in reducing stress concentration in implants inserted at bone level [61].

With further corroboration, an *in vitro* photoelastic analysis demonstrated that the strain distribution in the peri-radicular area of teeth, supported by an occlusal appliance, can be mitigated during parafunctional loading. In addition, the milled occlusal appliance, made with CAD/CAM, provided the best morphological adaptation and transferred lower strain to the bone areas, as compared to the other evaluated appliances [62].

With the consideration of a 3-unit implant-supported prostheses, a 3D-FEA investigation evaluated the biomechanical behavior of this treatment modality under parafunctional forces with and without an occlusal appliance. The data illustrated that an occlusal splint improved the biomechanical behavior of the prostheses, by reducing stress in the abutment screws and stress and strain in the bone tissue. However, it was also demonstrated that the occlusal splint was not 100% effective to avoid the biomechanical benefits of splinting crowns [63].

Figure 15 depicts the stress generated by the same occlusal load applied on the crowns or on the occlusal splint. The recommendation of an appliance use should be part of the comprehensive treatment plan for patients rehabilitated with implants.

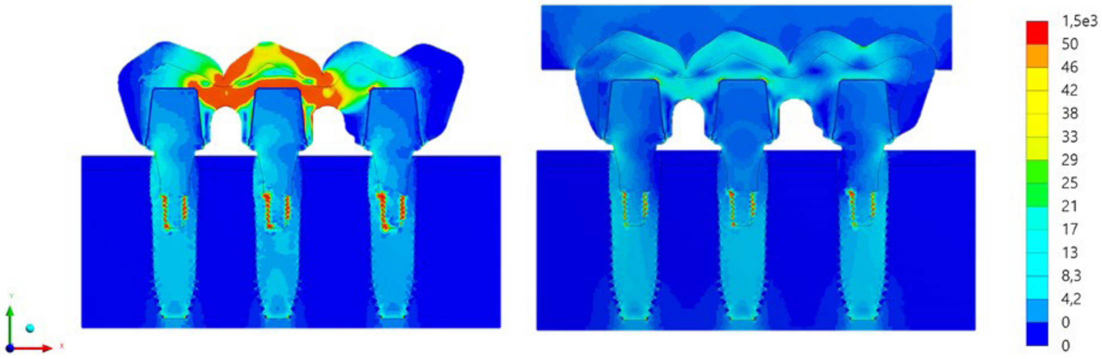

Figure 15 - Stress at a posterior bridge after 100 N load without and with a 4 mm occlusal splint made in acrylic resin.

LIMITATIONS

Among the different mechanical tools that can be applied to estimate the biomechanical behavior of implant-supported restorations, FEA consists in a reliable numerical method to assess complex mechanical conditions. This mathematical approach can identify the areas of highest stress magnitude, which coincide to the areas that are most prone to failure in prostheses and implants [64,65]. Although a theoretical method, FEA provides accurate results by dividing a complex geometry into a finite number of elements and using the boundary conditions and physical properties that correspond to the evaluated restoration [66].

In addition, this method is a non-invasive, non-destructive analysis, with reproducibility and provides the advantage to evaluate clinical conditions that may be difficult with *in vitro* methods [66-68]. This report, that utilized stress maps, illustrated important biomechanical principles that should be considered in implant dentistry. However, this is not a numerical study and the present figures were made only for illustrative purpose.

CONCLUSIONS

Due to the constant development and expansion of implant dentistry field, the clinician and technician have many more decisions to make that impact on the predictability and success of treatment. Stress analysis provides important insights in the rehabilitation workflow that provides critical information regarding implant treatment decision-making. The more information the clinician and technician have, the better is the decision making process, which would ultimately improve the clinical outcome for the patient.

Author's Contributions

GSA: Conceptualization, Methodology, Formal Analysis, Investigation, Resources, Data Curation, Writing – Original Draft Preparation, Visualization. LK: Conceptualization, Investigation, Writing – Original Draft Preparation, Writing – Review & Editing, Visualization. RLG: Investigation, Resources, Writing – Original Draft Preparation and Project Administration. DA: Conceptualization, Investigation, Resources, Writing – Original Draft Preparation and Visualization. AJF: Conceptualization, Methodology, Software, Validation, Formal Analysis, Investigation, Resources, Data Curation, Writing – Review & Editing, Visualization, Supervision, Project Administration and Funding Acquisition. JPMT: Conceptualization, Methodology, Software, Validation, Formal Analysis, Investigation, Resources, Data Curation, Writing – Review & Editing, Visualization, Supervision, Project Administration and Funding Acquisition.

Conflict of interest

The authors declare no conflict of interest.

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Regulatory Statement

Not applicable.

REFERENCES

1. Manea A, Bran S, Dinu C, Rotaru H, Barbur I, Crisan B, et al. Principles of biomechanics in oral implantology. Med Pharm Rep. 2019;92(Suppl 3):S14-9. http://dx.doi.org/10.15386/mpr-1512. PMid:31989104.

2. Bushra S, Khierla L, Guindy E, Fahmy J, El Nahass H. Esthetic patient satisfaction, marginal bone loss and peri-implant tissue success in esthetic zone: systematic review. Braz Dent Sci. 2022;25(1):e2514. http://dx.doi.org/10.4322/bds.2022.e2514.

3. Thome G, Caldas W, Vianna CP, Cartelli CA, Trojan LC. Surgical and prosthetic outcomes of 967 implants under immediate or delayed loading in full-arch rehabilitation: a retrospective study with up to 5 years of follow-up. Braz Dent Sci. 2021;24(3):1-7. http://dx.doi.org/10.14295/bds.2021.v24i3.2403.

4. Jingade RRK, Rudraprasad IV, Sangur R. Biomechanics of dental implants: a FEM study. J Indian Prosthodont Soc. 2005;5(1):18. http://dx.doi.org/10.4103/0972-4052.16336.

5. Sailer I, Karasan D, Todorovic A, Ligoutsikou M, Pjetursson BE. Prosthetic failures in dental implant therapy. Periodontol 2000. 2022;88(1):130-44. http://dx.doi.org/10.1111/prd.12416. PMid:35103329.

6. Salvi GE, Brägger U. Mechanical and technical risks in implant therapy. Int J Oral Maxillofac Implants. 2009;24(Suppl):69-85. PMid:19885435.

7. Elsayed MD, Biomechanical factors that influence the bone-implant-interface. Res Rep Oral Maxillofac Surg. 2019;3:023. http://dx.doi.org/10.23937/2643-3907/1710023.

8. Acharya PH, Patel VV, Duseja SS, Chauhan VR. Comparative evaluation of peri-implant stress distribution in implant protected occlusion and cuspally loaded occlusion on a 3 unit implant supported fixed partial denture: A 3D finite element analysis study. J Adv Prosthodont. 2021;13(2):79-88. http://dx.doi.org/10.4047/jap.2021.13.2.79. PMid:34025956.

9. Topkaya T, Solmaz MY. The effect of implant number and position on the stress behavior of mandibular implant retained overdentures: A three-dimensional finite element analysis. J Biomech. 2015;48(10):2102-9. http://dx.doi.org/10.1016/j.jbiomech.2015.03.006. PMid:25862522.

10. Silveira MPM, Campaner LM, Bottino MA, Nishioka RS, Borges ALS, Tribst JPM. Influence of the dental implant number and load direction on stress distribution in a 3-unit implant-supported fixed dental prosthesis. Dent Med Probl. 2021;58(1):69-74. http://dx.doi.org/10.17219/dmp/130847. PMid:33687804.

11. Tribst JPM, Dal Piva AMO, Borges ALS, Bottino MA. Effect of implant number and height on the biomechanics of full arch prosthesis. Braz J Oral Sci. 2018;17:e18222. http://dx.doi.org/10.20396/bjos.v17i0.8653837.

12. Aalaei S, Abedi P, Niknami S, Taghavi F, Damghani FT. The effect of attachment types and implant level on the stress distribution in a mandibular overdenture: a 3D finite element analysis. Braz Dent Sci. 2022;25(3):e3355. http://dx.doi.org/10.4322/bds.2022.e3355.

13. Hong HR, Pae A, Kim Y, Paek J, Kim H-S, Kwon K-R. Effect of implant position, angulation, and attachment height on peri-implant bone stress associated with mandibular two-implant overdentures: a finite element analysis. Int J Oral Maxillofac Implants. 2012;27(5):e69-76. PMid:23057045.

14. Lopes DM, Nishyama R, Steagall W Jr, Tamaki R, Tortamano P No. Impact of different scan strategies and implant angulation on impression accuracy of full arch multiple implant: an in vitro study. Braz Dent Sci. 2022;25(1):e3006. http://dx.doi.org/10.4322/bds.2021.e3006.

15. Botros M, Kamal Adbel Gaber H, Abbas E, El-Mofty M, Bissar M. Split-block graft versus Cortico-cancellous block graft for horizontal ridge augmentation: Cone Beam Computed Tomography and Histomorphometric study. Braz Dent Sci. 2021;24(3):1-12. http://dx.doi.org/10.14295/bds.2021.v24i3.2464.

16. Demachkia AM, Sichi LGB, Rodrigues JVM, Nogueira L Jr, Araújo RM, Ramos NC, et al. Implant-supported restoration with straight and angled hybrid abutments: Digital image correlation and 3D-finite element analysis. Eur J Gen Dent. 2022;11(1):23-31. https://doi.org/10.1055/s-0042-1744362.

17. Reis FCS, Brandt WC, Boaro LCC, Miranda ME. Stress analysis of a single prosthesis on a poorly positioned implant. Res Soc Dev. 2021;10(11):e579101119815. http://dx.doi.org/10.33448/rsd-v10i11.19815.

18. Sousa MP, Tribst JPM, de Oliveira Dal Piva AM, Borges ALS, de Oliveira S, da Cruz PC. Capacity to maintain placement torque at removal, single load-to-failure, and stress concentration of straight and angled abutments. Int J Periodontics Restorative Dent. 2019;39(2):213-8. http://dx.doi.org/10.11607/prd.3998. PMid:30794257.

19. Özcan M, Höhn J, De Araújo GM, Moura DD, Souza R. Influence of testing parameters on the load-bearing capacity of prosthetic materials used for fixed dental prosthesis: A systematic review and meta-analysis. Braz Dent Sci. 2018;21(4):470-90. http://dx.doi.org/10.14295/bds.2018.v21i4.1652.

20. Elter B, Alada A, Çömlekolu ME, Çömlekolu MD. Replacement of maxillary lateral incisors with digitally manufactured single tooth retained all-ceramic pontics: a clinical report. Braz Dent Sci. 2022;25(1):e2856. http://dx.doi.org/10.4322/bds.2022.e2856.

21. Tribst JPM, Dal Piva AMO, Bottino MA, Nishioka RS, Borges ALS, Özcan M. Digital Image Correlation and finite element analysis of bone strain generated by implant-retained cantilever fixed prosthesis. Eur J Prosthodont Restor Dent. 2020;28(1):10-7. http://dx.doi.org/10.1922/EJPRD_1941Tribst08. PMid:31638348.

22. Seelig da Cunha K, De Lima Coltro MP, Drummond LG, Ozkomur A, Villarinho EA, Teixeira ER, et al. Biomechanical variables affect peri-implant bone loss in implant-supported fixed complete dentures: a methodological and prospective study. J Prosthodont Res. 2022; ahead of print. http://dx.doi.org/10.2186/jpr.JPR_D_21_00254. PMid:35613872.

23. Tribst JPM, Campanelli de Morais D, Melo de Matos JD, Lopes GRS, Dal Piva AMO, Souto Borges AL, et al. Influence of framework material and posterior implant angulation in full-arch all-on-4 implant-supported prosthesis stress concentration. Dent J (Basel). 2022;10(1):12. http://dx.doi.org/10.3390/dj10010012. PMid:35049610.

24. Guichet DL, Yoshinobu D, Caputo AA. Effect of splinting and interproximal contact tightness on load transfer by implant restorations. J Prosthet Dent. 2002;87(5):528-35. http://dx.doi.org/10.1067/mpr.2002.124589. PMid:12070516.

25. Sasaki T, Nakata H, Suzuki A, Hada T, Kasugai S, Kuroda S. Comparison of splinted and non-splinted superstructures of three implants placed in a mandibular distal extension model with missing teeth using modal analysis. J Mech Behav Biomed Mater. 2020;112:104050. http://dx.doi.org/10.1016/j.jmbbm.2020.104050. PMid:32947100.

26. Lemos CAA, Verri FR, Santiago JF Jr, de Souza Batista VE, Kemmoku DT, Noritomi PY, et al. Splinted and nonsplinted crowns with different implant lengths in the posterior maxilla by three-dimensional finite element analysis. J Healthc Eng. 2018;2018:3163096. http://dx.doi.org/10.1155/2018/3163096. PMid:30254726.

27. Ahmed MAM, Hamdy AM, Fattah GA, Effadl AKA. Prosthetic design and restorative material effect on the biomechanical behavior of dental implants: strain gauge analysis. Braz Dent Sci. 2022;25(3):e3380. http://dx.doi.org/10.4322/bds.2022.e3380.

28. da Rocha Ferreira JJ, Machado LFM, Oliveira JM, Ramos JCT. Effect of crown-to-implant ratio and crown height space on marginal bone stress: a finite element analysis. Int J Implant Dent. 2021;7(1):81. http://dx.doi.org/10.1186/s40729-021-00368-1. PMid:34467461.

29. Fathi A, Rismanchian M, Khodadadi R, Dezaki SN. Does the crown-implant ratio affect the survival and complications of implant-supported prostheses? A systematic review. J Prosthet Dent. 2022;S0022-3913(22):00175-5. http://dx.doi.org/10.1016/j.prosdent.2022.03.007. PMid:35469647.

30. Rangert BR, Sullivan RM, Jemt TM. Load factor control for implants in the posterior partially edentulous segment. Int J Oral Maxillofac Implants. 1997;12(3):360-70. PMid:9197101.

31. Nissan J, Ghelfan O, Gross O, Priel I, Gross M, Chaushu G. The effect of crown/implant ratio and crown height space on stress distribution in unsplinted implant supporting restorations. J Oral Maxillofac Surg. 2011;69(7):1934-9. http://dx.doi.org/10.1016/j.joms.2011.01.036. PMid:21530042.

32. Verri FR, Batista VES, Santiago JF Jr, Almeida DAF, Pellizzer EP. Effect of crown-to-implant ratio on peri-implant stress: a finite element analysis. Mater Sci Eng C Mater Biol Appl. 2014;45:234-40. http://dx.doi.org/10.1016/j.msec.2014.09.005. PMid:25491825.

33. Jalalian E, Yousofi Z. Comparing torque loss in standard implants and short implants with increased vertical cantilever abutments: an in vitro study. Braz Dent Sci. 2021;24(1):1-8. https://doi.org/10.14295/bds.2021.v24i1.1985.

34. Duyck J, Vandamme K. The effect of loading on peri-implant bone: a critical review of the literature. J Oral Rehabil. 2014;41(10):783-94. http://dx.doi.org/10.1111/joor.12195. PMid:24889500.

35. Rossi AC, Freire AR, Ferreira BC, Faverani LP, Okamoto R, Prado FB. Effects of premature contact in maxillary alveolar bone in rats: relationship between experimental analyses and a micro scale FEA computational simulation study. Clin Oral Investig. 2021;25(9):5479-92. http://dx.doi.org/10.1007/s00784-021-03856-1. PMid:33641062.

36. Djebbar N, Serier B, Bouiadjra BB, Benbarek S, Drai A. Analysis of the effect of load direction on the stress distribution in dental implant. Mater Des. 2010;31(4):2097-101. http://dx.doi.org/10.1016/j.matdes.2009.10.042.

37. Ausiello P, Tribst JPM, Ventre M, Salvati E, di Lauro AE, Martorelli M, et al. The role of cortical zone level and prosthetic platform angle in dental implant mechanical response: a 3D finite element analysis. Dent Mater. 2021;37(11):1688-97. http://dx.doi.org/10.1016/j.dental.2021.08.022. PMid:34497022.

38. Watanabe F, Hata Y, Komatsu S, Ramos TC, Fukuda H. Finite element analysis of the influence of implant inclination, loading position, and load direction on stress distribution. Odontology. 2003;91(1):31-6. http://dx.doi.org/10.1007/s10266-003-0029-7. PMid:14505187.

39. Datte CE, Rodrigues VA, Datte FB, Lopes GRS, Borges ALS, Nishioka RS. The effect of different bone level and prosthetic connection on the biomechanical response of unitary implants: strain gauge and finite element analyses. Int J Adv Eng Res Sci. 2021;8(2):218-24. http://dx.doi.org/10.22161/ijaers.82.28.

40. Manchikalapudi G, Basapogu S. Finite Element Analysis of effect of cusp inclination and occlusal contacts in PFM and PEEK implant-supported crowns on resultant stresses. Med J Armed Forces India. 2022;78(1):80-7. http://dx.doi.org/10.1016/j.mjafi.2020.11.014. PMid:35035048.

41. Borges ALS, Tribst JPM, de Lima AL, Dal Piva AMO, Özcan M. Effect of occlusal anatomy of CAD/CAM feldspathic posterior crowns in the stress concentration and fracture load. Clin Exp Dent Res. 2021;7(6):1190-6. http://dx.doi.org/10.1002/cre2.454. PMid:34240808.

42. Mohamed AM, Askar MG, El Homossany ME. Stresses induced by one piece and two piece dental implants in All-on-4® implant supported prosthesis under simulated lateral occlusal loading: non linear finite element analysis study. BMC Oral Health. 2022;22(1):196. http://dx.doi.org/10.1186/s12903-022-02228-9. PMid:35599323.

43. Silva GC, de Andrade GM, Coelho RC, Cornacchia TM, de Magalhães CS, Moreira AN. Effects of screw- and cement-retained implant-supported prostheses on bone: a nonlinear 3-D finite element analysis. Implant Dent 2015;24(4):464-71. http://doi.org/10.1097/ID.0000000000000278. PMID: 25985378.

44. Hebel KS, Gajjar RC. Cement-retained versus screw-retained implant restorations: achieving optimal occlusion and esthetics in implant dentistry. J Prosthet Dent. 1997;77(1):28-35. http://dx.doi.org/10.1016/S0022-3913(97)70203-8. PMid:9029462.

45. Millen C, Brägger U, Wittneben J-G. Influence of prosthesis type and retention mechanism on complications with fixed implant-supported prostheses: a systematic review applying multivariate analyses. Int J Oral Maxillofac Implants. 2015;30(1):110-24. http://dx.doi.org/10.11607/jomi.3607. PMid:25615920.

46. Michalakis KX, Hirayama H, Garefis PD. Cement-retained versus screw-retained implant restorations: a critical review. Int J Oral Maxillofac Implants. 2003;18(5):719-28. PMid:14579961.

47. Silva GC, Cornacchia TM, de Magalhães CS, Bueno AC, Moreira AN. Biomechanical evaluation of screw- and cement-retained implant-supported prostheses: a nonlinear finite element analysis. J Prosthet Dent. 2014;112(6):1479-88. http://dx.doi.org/10.1016/j.prosdent.2014.06.010. PMid:25062583.

48. Tribst JPM, Dal Piva AMO, Gonçalves NIÊ, Borges ALS, Bottino MA, Kleverlaan CJ. Polymerization shrinkage and push-out bond strength of different composite resins for sealing the screw-access hole on implant-supported crowns. J Adhes Dent. 2020;22(5):523-30. http://dx.doi.org/10.3290/j.jad.a45182. PMid:33073783.

49. Weber HP, Kim DM, Ng MW, Hwang JW, Fiorellini JP. Peri-implant soft-tissue health surrounding cement- and screw-retained implant restorations: a multi-center, 3-year prospective study. Clin Oral Implants Res. 2006;17(4):375-9. http://dx.doi.org/10.1111/j.1600-0501.2005.01232.x. PMid:16907767.

50. Gaddale R, Mishra SK, Chowdhary R. Complications of screw- and cement-retained implant-supported full-arch restorations: a systematic review and meta-analysis. Int J Oral Implantol (Berl). 2020;13(1):11-40. PMid:32186285.

51. Lee H, Jo M, Sailer I, Noh G. Effects of implant diameter, implant-abutment connection type, and bone density on the biomechanical stability of implant components and bone: a finite element analysis study. J Prosthet Dent. 2022;128(4):716-28. http://dx.doi.org/10.1016/j.prosdent.2020.08.042. PMid:33685654.

52. Matsuoka T, Nakano T, Yamaguchi S, Ono S, Watanabe S, Sato T, et al. Effects of implant-abutment connection type and inter-implant distance on inter-implant bone stress and microgap: three-dimensional finite element analysis. Materials (Basel). 2021;14(9):2421. http://dx.doi.org/10.3390/ma14092421. PMid:34066506.

53. Tribst JP, Dal Piva AM, Rodrigues VA, Borges AL, Nishioka RS. Stress and strain distributions on short implants with two different prosthetic connections-an in vitro and in silico analysis. Braz Dent Sci. 2017;20(3):101-9. http://dx.doi.org/10.14295/bds.2017.v20i3.1433.

54. Maminskas J, Puisys A, Kuoppala R, Raustia A, Juodzbalys G. The prosthetic influence and biomechanics on Peri-implant strain: a systematic literature review of finite element studies. J Oral Maxillofac Res. 2016;7(3):e4. http://dx.doi.org/10.5037/jomr.2016.7304. PMid:27833729.

55. Rodrigues EDS, Benetti P, Carli JPD, Paranhos LR, Santos PL, Linden MS. A comparison of torque stress on abutment screw of external hexagon and Morse taper implant. J Contemp Dent Pract. 2018;19(11):1306-11. http://dx.doi.org/10.5005/jp-journals-10024-2423. PMid:30602632.
56. Tribst JPM, Dal Piva AMO, Borges ALS, Anami LC, Kleverlaan CJ, Bottino MA. Survival probability, weibull characteristics, stress distribution, and fractographic analysis of polymer-infiltrated ceramic network restorations cemented on a chairside titanium base: an in vitro and in silico study. Materials (Basel). 2020;13(8):1879. http://dx.doi.org/10.3390/ma13081879. PMid:32316360.
57. Gomez-Meda R, Esquivel J, Blatz MB. The esthetic biological contour concept for implant restoration emergence profile design. J Esthet Restor Dent. 2021;33(1):173-84. http://dx.doi.org/10.1111/jerd.12714. PMid:33470498.
58. Kim M-K, Lee J-H, Ahn S-G, Kim K-A, Seo J-M. Regeneration of emergence profile with soft tissue graft and wide computer aided design/computer aided mamufacturing abutments: a clinical report. J Dent Rehabil Appl Sci. 2015;31(4):364-70. http://dx.doi.org/10.14368/jdras.2015.31.4.364.
59. Miola Siqueira de Oliveira JP, Corso PFCL, De Oliveira GC, Scariot R, Costa DL. Atrophic jaw fracture and predictability in oral rehabilitation: case report. Braz Dent Sci. 2020;23(3):1-6. http://dx.doi.org/10.14295/bds.2020.v23i3.1922.
60. Refaie A, Zohdy M, Aboelfadl A, Wahsh M. Effect of different immediate implant loading protocols on Peri-implant soft tissue health. Braz Dent Sci. 2020;23(4):1-7. http://dx.doi.org/10.14295/bds.2020.v23i4.1998.
61. Borges Radaelli MT, Idogava HT, Spazzin AO, Noritomi PY, Boscato N. Parafunctional loading and occlusal device on stress distribution around implants: a 3D finite element analysis. J Prosthet Dent. 2018;120(4):565-72. http://dx.doi.org/10.1016/j.prosdent.2017.12.023. PMid:29724560.
62. Arcas LPB, Baroudi K, Silva-Concílio LR, Claro CAA, Amaral M. Effect of different fabrication methods of occlusal devices on periradicular stress distribution: a photoelastic analysis. J Prosthet Dent. 2021;S0022-3913(21):00352-8. http://dx.doi.org/10.1016/j.prosdent.2021.06.037. PMid:34344528.
63. Silva LS, Verri FR, Lemos CAA, Martins CM, Pellizzer EP, de Souza Batista VE. Biomechanical effect of an occlusal device for patients with an implant-supported fixed dental prosthesis under parafunctional loading: a 3D finite element analysis. J Prosthet Dent. 2021;126(2):223.e1-8. http://dx.doi.org/10.1016/j.prosdent.2021.04.024. PMid:34099274.
64. Archangelo KC, Penteado MM, Dal Piva AMO, Nogueira AS, Tribst JPM, Borges ALS. Stress distribution and failure load of multilayer and monolayer glass ceramic. Braz Dent Sci. 2019;22(1):17-22. http://dx.doi.org/10.14295/bds.2019.v22i1.1611.
65. Jurema ALB, Penteado MM, Tribst JPM, Caneppele TMF, Borges ALS. Effect of glass-fiber post on the biomechanical behavior of teeth with direct veneers. Braz Dent Sci. 2020;23(3). http://dx.doi.org/10.14295/bds.2020.v23i3.1969.
66. Paes TJ Jr, Tribst JP, Piva D, Figueiredo D, Borges VM, Inagati AL. Influence of fibromucosa height and loading on the stress distribution of a total prosthesis: a finite element analysis. Braz Dent Sci. 2021;24(2):1-7. http://dx.doi.org/10.14295/bds.2021.v24i2.2144.
67. Meirelles LCF, Pierre FZ, Tribst JPM, Pagani C, Bresciani E, Borges ALS. Influence of preparation design, restorative material and load direction on the stress distribution of ceramic veneer in upper central incisor. Braz Dent Sci. 2021;24(3):1-13. http://dx.doi.org/10.14295/bds.2021.v24i3.2494.
68. Nabih SM, Ibrahim NIM, Elmanakhly AR. Mechanical and thermal stress analysis of hybrid ceramic and lithium disilicate based ceramic CAD-CAM inlays using 3-D finite element analysis. Braz Dent Sci. 2021;24(3):1-10. http://dx.doi.org/10.14295/bds.2021.v24i3.2453.

João Paulo Mendes Tribst
(Corresponding address)
University of Amsterdam and Vrije Universiteit Amsterdam, Academic Centre for Dentistry Amsterdam, Department of Oral Regenerative Medicine, Amsterdam, The Netherlands
Email: j.p.mendes.tribst@acta.nl

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