

Influence of Implant Position in Implant-Assisted Removable Partial Denture: A Three-Dimensional Finite Element Analysis

Octavi Ortiz-Puigpelat, DDS, PhD,¹ Aida Lázaro-Abdulkarim, DDS,¹ Javier-María de Medrano-Reñé, DDS,² Jordi Gargallo-Albiol, DDS, PhD, EBOS,² Josep Cabratosa-Termes, DMD, PhD,² & Federico Hernández-Alfaro, MD, DDS, PhD, FEBOMS¹

¹Department of Oral and Maxillofacial Surgery, Universitat Internacional de Catalunya, Barcelona, Spain

²Department of Prosthodontics, Universitat Internacional de Catalunya, Barcelona, Spain

Keywords

Dental implants; finite element analysis; removable partial dentures; resilient attachment.

Correspondence

Dr. Octavi Ortiz-Puigpelat, Department of Oral and Maxillofacial Surgery, Universitat Internacional de Catalunya, C/Josep Trueta s/n 08195, St. Cugat del Vallès, Barcelona, Spain. E-mail: octavi_ortiz@hotmail.com.

The authors declare no conflicts of interest related to this study.

Accepted August 13, 2017

doi: 10.1111/jopr.12722

Abstract

Purpose: To determine the ideal position of a dental implant to assist a posterior extended partial removable dental prosthesis (PRDP), through stress values, displacement values, and deformation of periodontal ligament (PDL).

Materials and Methods: A finite element analysis of different implant positions was analyzed using a 3D mandible model from a human patient. Test models were created: model A (implant in second molar area), model B (implant in the first molar area), and model C (implant in premolar area). A control model without implant support was also created. Overall displacement values, von Mises stress distribution maps, and nonlinear deformations were evaluated.

Results: Some differences could be observed between test models. The introduction of an implant in the edentulous area, unlike a conventional removable partial denture without implant support, decreases stress values in the biological structures such as: mandible, tooth, soft tissue, and PDL. Placing the implant in the first molar area resulted in improved displacement values, and reduced maximum stress values at the peri-implant bone area, metal structure, and implant were observed.

Conclusions: Within the limitations of this study we can conclude that placing the implant in the position of the first molar improves biomechanical behavior of implant-assisted PRDPs.

The use of dental implants to support or assist distal extension partial removable dental prostheses (PRDPs) has been well documented.¹⁻⁷ Several clinical benefits of implant-assisted PRDPs (IAPRDPs) are claimed by these studies such as: increased retention of the denture and therefore limiting the lateral and vertical displacement of the PRDP, efficient distribution of masticatory forces along the PRDP and the remaining teeth, and reduction of the resorption process that occurs below the distal base saddle.⁸ Moreover, recent well-designed prospective clinical studies recommend the use of IAPRDPs over the use of conventional PRDPs, since IAPRDPs can improve chewing capacity and patient satisfaction.^{9,10}

Implant location along the distal extension area of the PRDP has been a source of debate both in clinical and in vitro studies, as it may play a crucial role in the force distribution of the IAPRDP and therefore influence the clinical effects of such treatment modality.^{1-8,12} Distalized position (second molar) or middle position (first molar and second premolar) for ideal implant position have been claimed in clinical and in vitro studies to increase stability of the IAPRDP.^{3,4,9} However, a preferred position has not been clarified.¹⁰

Finite element analysis (FEA) has been and is still widely used for predicting the biomechanical behavior of dental implants.¹¹ FEA applied to IAPRDPs has been used in numerous studies.^{5,12-19} Memari et al¹² conducted a 3D FEA analysis, which reinforced the hypothesis that an implant placed in the first molar would improve the biomechanical behavior of an IAPRDP. Their findings showed that, in contrast to other clinical and in vitro studies, the position of the implant in the first molar was the one that offered the least displacement values and therefore the best distribution of forces over the remaining teeth and along the alveolar ridge; however, this study was based on a simplified 3D model and did not consider the natural geometry of a real patient. This could lead to some assumptions that would reduce the predictive accuracy of the FEA model.¹¹ At present, the literature does not include 3D FEA studies based on real patient models that analyze the ideal position of the implants along the edentulous ridge in IAPRDPs.

The aim of this study is to clarify which implant position in Kennedy class 1 IAPRDPs generates an improved biomechanical behavior on the different biological and nonbiological structures, using 3D FEA.

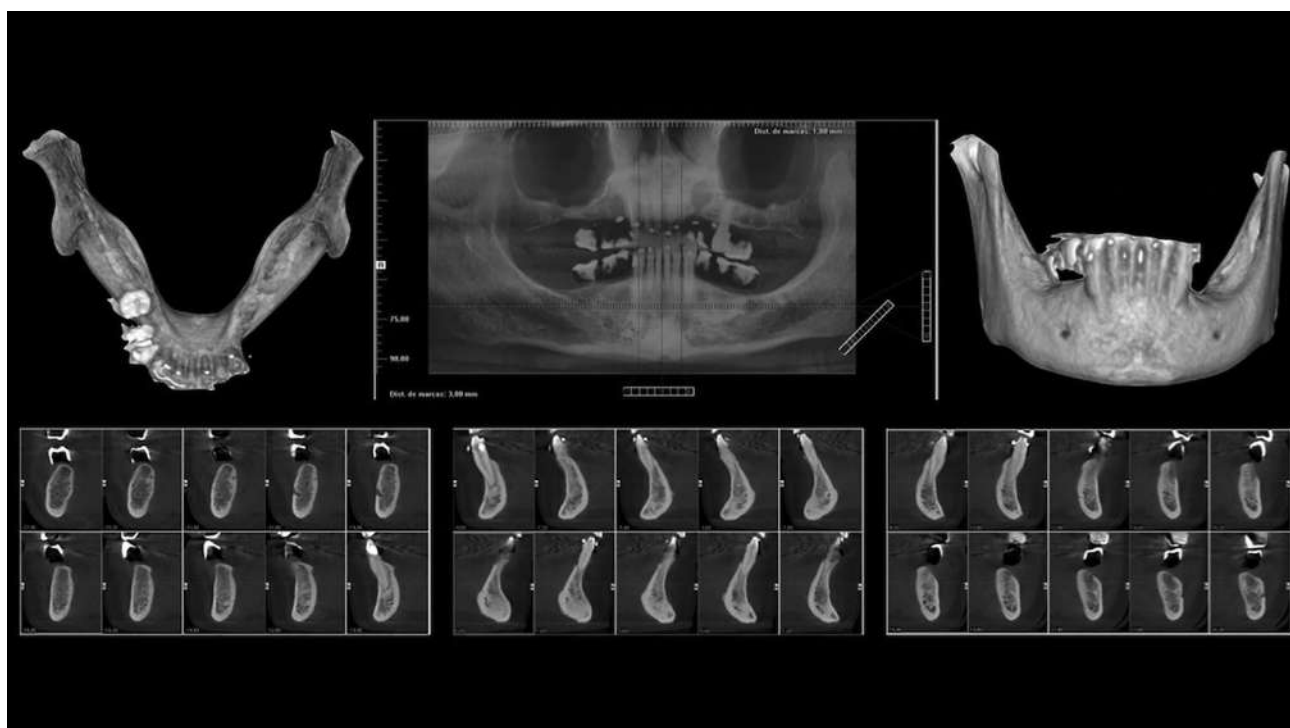


Figure 1 Selected CBCT of patient. Cross sectional views were obtained to check for bone availability of posterior alveolar ridge.

Materials and methods

This study was approved by the Research Ethics Committee (REC) of the School of Dentistry at the Universitat Internacional de Catalunya (UIC).

Obtaining the digital models

To work with a realistic model, a 3D cone beam computerized tomography (CBCT) scans were selected among the records of patients who underwent dental implant therapy in the UIC dental clinic. The selection criteria were that the patient had to have posterior bilateral mandibular edentulism with enough available bone to place standard dental implants without the need of any kind of bone regeneration. The selected CBCT scan was from a 53-year-old male patient with a Kennedy class 1 mandibular partial edentulism (Fig 1). Then, a stereolithographic model of the mandible was printed (Fig 2A) to fabricate a 2-mm thick soft tissue structure (Fig 2B). A conventional PRDP with a lingual bar connector, minor connectors, retentive clasps, occlusal rest, and reciprocal clasp was fabricated (Fig 2C). Once the PRDP was obtained, all models were digitalized by an optical scanner (Steinbichler Comet I3d 5m; Steinbichler Optotechnik GmbH, Neubeuern, Germany) (Figs 3A and B).

The implant chosen for this study was an Ankylos implant (Dentsply Sirona Inc., York, PA); 3.5-mm diameter, 11-mm long. These dimensions represent one of the most common implant dimensions used in implantology.²⁰ Also, a conical internal connection implant was chosen, since it demonstrated good clinical results in abutment fit, stability, and seal performance.²¹ The retentive element chosen for this study was the Locator®

abutment (Zest Anchors, LLC, Carlsbad, CA), which is a widely used retentive system chosen for its ease of use, repair, and replacement. Additionally, different connections and heights that can adapt to different prosthetic situations are available.^{22,23} The digital models of the implant and the Locator abutment were obtained directly from the manufacturers with a stereolithography (STL) format file, so precise models were used in the FEA (Fig 3C).

Digital model preparation

The different digital models were assembled into one model using SolidWorks software v14 (Dassault Systèmes SolidWorks Corp., Waltham, MA). After assembly, a simplification was needed to reduce calculation time. Such simplification was done using the same software and consisted in reducing the size of the mandible in length and sectioning it sagittally to obtain the left mandibular quadrant (Fig 4).

Since the periodontal ligament (PDL) could not be differentiated in the CBCT scan, it was also generated with the SolidWorks software. Thickness ranged from 0.125 to 0.250 mm following a previously published study.²⁴ In this study this ligament was only assigned to the canine, as it would be the only tooth in direct contact with the PRDP.

Study models

After preparation, the test models were created depending on the different implant positions along the edentulous ridge: model A, implant placed in the second molar area (Fig 5A); model B, implant placed in the first molar area (Fig 5B); and

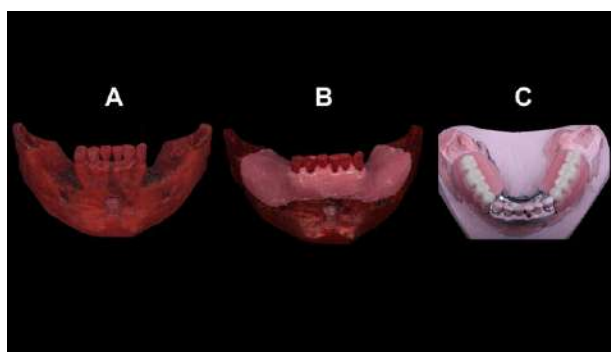


Figure 2 Stereolithographic model of mandible. (A) Sintered model of mandible. (B) Sintered model with soft tissue. (C) Conventional RDP fabricated.

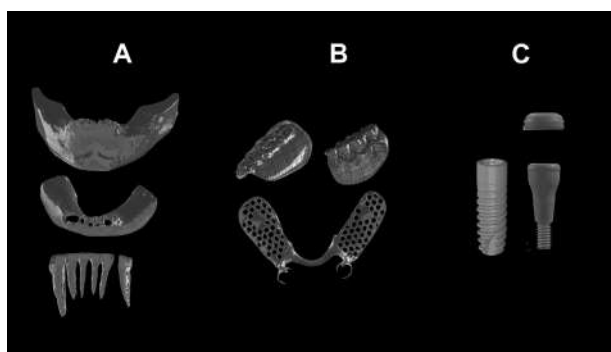


Figure 3 All digital models obtained for FEA. (A) Biological models of mandible, soft tissue and teeth. (B) Models related to PRDP, separation between resin base models and metal framework model. (C) Set of models of implant and the Locator abutment with its metal attachment.

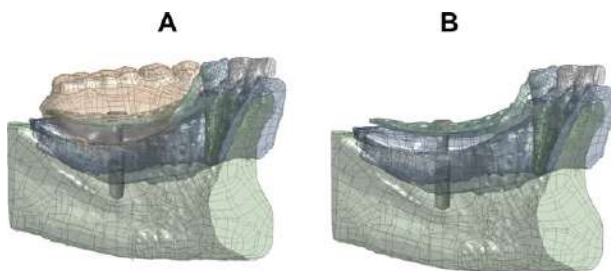


Figure 4 Simplified model with all different structures assembled. (A) Simplified model with resin base of PRDP. (B) Simplified model without resin base to check position of Locator abutment.

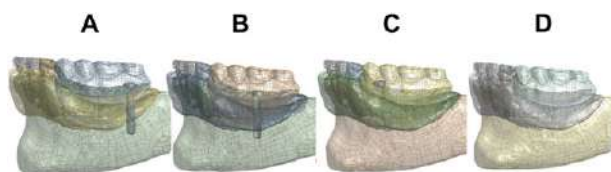


Figure 5 Study models. (A) Model with implant placed in the area of second molar. (B) Model with implant placed in position of first molar. (C) Model with implant position in intermediate area of premolars. (D) Control model without implants.

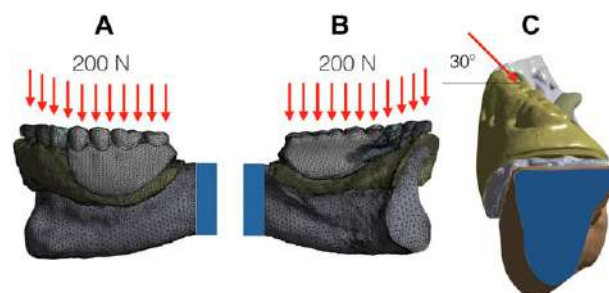


Figure 6 Tetrahedral mesh shape of model, magnitude, direction, and inclination of masticatory forces used for FEA. (A) Magnitude force of 200 N directed towards occlusal surface. (B) Lingual view. (C) Oblique inclination of 30° angle in relation with occlusal plane. Blue area in A, B, and C indicating fixation of model to allow rotational movement of mandible.

Table 1 Different thicknesses of mesh used depending on different structures analyzed

Structures	Mesh thickness (mm)
Jawbone	2
Teeth	1
Periodontal ligament	0.2
Soft tissue	1.5
Metal structure of PRPD	1
Resin base of PRPD	1.5
Implant and Locator abutment	0.6

model C, implant placed in the premolar area (Fig 5C). Also, a control model was generated with a conventional RDP without implant support (Fig 5D).

The meshes of the different study models were generated with SolidWorks software, and a tetrahedral form was selected for the FEA (Figs 6A and B). The thickness of the mesh was different for each structure to be analyzed, and ranged from 0 to 2 mm (Table 1).

Physical properties and interaction between structures and masticatory forces

The different physical properties of all materials used were considered isotropic and expressed in two separate constants: Young's elasticity modulus in MPa and Poisson's ratio.^{11,25} Some physical properties were obtained from a similar study by Pellizzer *et al.*¹⁵ Physical properties of bone were made by mean values between cortical and trabecular bone (Table 2). The interaction of the different structures that composed the models of the study was considered as bonded.

To simulate a realistic masticatory process, a 200 N magnitude force with a bucco-lingual direction of 30° to the occlusal plane was applied to the models following previous studies in the literature^{26,27} (Fig 6). The displacement of all models was restrained at the distal part of the mandible, allowing an anterior-inferior movement in an attempt to simulate a rotational temporomandibular joint (TMJ) movement (Fig 6).

Table 2 Physical properties of materials used

Materials	Young's modulus (GPa)	Poisson's coefficient
Jawbone	4.4525	0.3
Teeth*	18.6	0.31
Alveolar mucosa*	0.68	0.45
Titanium implant*		
Locator® retainer*	103.4	0.35
Chrome-cobalt metal structure*	206.9	0.33
Acrylic resin*	8.3	0.28
Nylon retentive part of the Locator*	2.4	0.39

*Material properties obtained from Pellizzer *et al*.¹⁵

Table 3 Maximum values of displacements, stress, and nonlinear deformation of the different structures obtained from each model

	Model A	Model B	Model C	Control
Total displacement (mm)	0.074	0.071	0.077	0.1
Mandible stress (MPa)	13.21	13.02	9.40	14.75
Metal framework stress (MPa)	135.7	87.30	65.31	104.3
Soft tissue stress (MPa)	2.6	3.2	3.3	3
Resin stress (MPa)	30.2	37	16	17.55
Tooth stress (MPa)	13.36	17.48	13.49	18.00
Implant stress (MPa)	123.24	83.55	224.1	—
Periodontal ligament stress (MPa)	0.103	0.105	0.103	0.102
Periodontal ligament deformation %	22	26	21	27

FEA calculation

The calculation method to simulate the behavior of the different materials was linear for all elements of the model, except for the PDL of the canine, which was established as nonlinear in geometry and in material composition, based on previously published studies.^{24,28} To evaluate the biomechanical behavior of the IAPRDP, values of displacements in mm, von Mises stress maps in MPa, and nonlinear strains in % of the different structures were considered. Descriptive analysis of the data obtained in the finite element simulation was performed.

Results

Table 3 shows the overall results obtained after conducting the FEA.

Overall displacements

Displacements were very similar in the different test models (model A: 0.074 mm; model B: 0.071 mm, and model C: 0.077 mm) (Figs 7A to C); however, they were different from the control model (0.1 mm) (Fig 7D). Model B obtained the lowest values and a greater distribution of such displacements (Fig 7B).

Mandible bone stress

Maximum stress values were: 13.21 MPa in model A, 13.02 MPa in model B, 9.40 MPa in model C, and 14.75 MPa in the control model (Fig 8). In the test models with the implant, stress concentrations were found in the interface between the implant and the prosthetic abutment (Figs 8A to C).

Soft tissue stress

Maximum stress values obtained in the soft tissue were 2.6 MPa in model A, 3.2 MPa in model B, 3.3 MPa in model C, and 3 MPa in the control model.

Tooth stress

In the canine tooth, the maximum stresses ranged from 13.36 to 18 MPa. In all models, these tensions were located on the distal area in contact with the PRDP. Stress was higher in the control model.

PDL stress and nonlinear deformation

The stress values found in the PDL were very similar: in model A, 0.103 MPa; in model B, 0.105 MPa; in model C, 0.103 MPa; and in the control model, 0.102 MPa (Fig 9). The location and the distribution of these were very similar in all models and were concentrated on the lingual and mesial aspects of the ligament. They are reported in Table 3 and Figure 10. In all models, these strains were located on the mesio-buccal aspect of the cervical portion of the ligament.

Metal framework and resin stress

Maximum stress values found in the metal framework are recorded in Table 3 and Figure 11. In the resin, the maximum stresses were very similar in models A and B. The control model and model C behaved in a similar way in terms of maximum stresses.

Implant stress

Stress values found in the implants are listed in Table 3 and Figure 12.

Discussion

Although FEA studies show an impressive capacity to investigate biomechanical behavior of dental implants and their surrounding tissues,¹¹ one of the main limitations is that due to the complexity of the geometry, composition, and dynamic behavior of biological structures, simplification of the working models is needed to reduce calculation time,¹¹ consequently making FEA studies less accurate in predicting biomechanical behavior. Therefore, simplification of the models has to be limited in order to obtain a more predictable FEA.²⁹

In this study simplification was applied in the model's size, the physical properties of bone, and the model's range of movements. Regarding the size of the model, only the left mandible quadrant was used instead of the entire mandible, since bilateral posterior partial edentulism was studied, and symmetric conditions were considered. The physical properties of bone

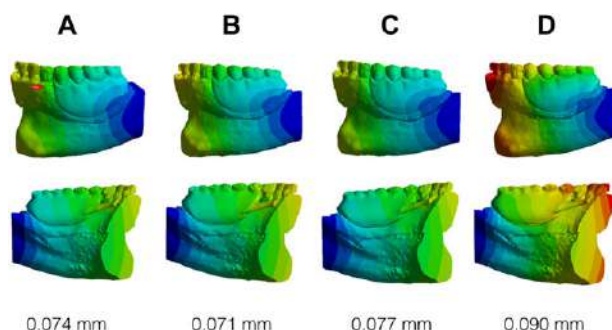


Figure 7 Overall displacement values and their distributions (maximum values in red, minimum values in blue).

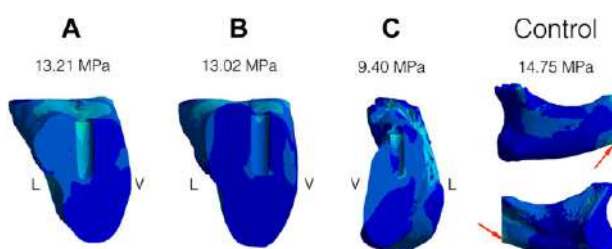


Figure 8 Von Mises stress map of mandible (maximum values in red, minimum values in blue). The sectional cuts of peri-implant bone of test models are shown. Vestibular (V) and lingual (L) sides are marked. Red arrow locates maximum stress.

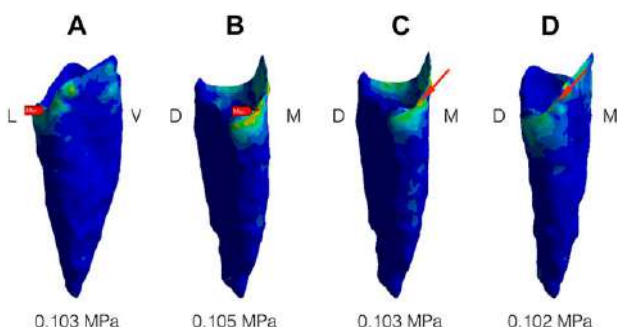


Figure 9 Von Mises stress map of PDL (maximum values in red, minimum values in blue). Mesial (M), distal (D), vestibular (V), and lingual (L) sides of PDL are marked. Red arrow locates maximum stress.

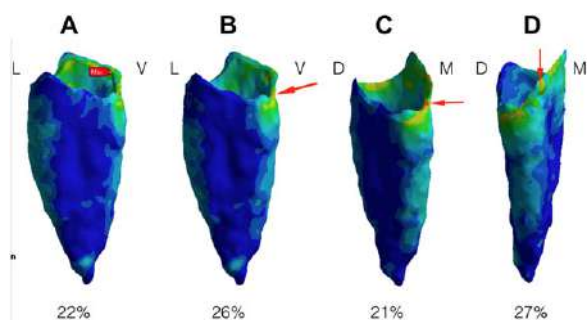


Figure 10 Maximum nonlinear strains and their distributions of PDL (maximum values in red, minimum values in blue). Mesial (M), distal (D), vestibular (V), and lingual (L) sides of PDL are marked. Red arrow locates maximum strain.

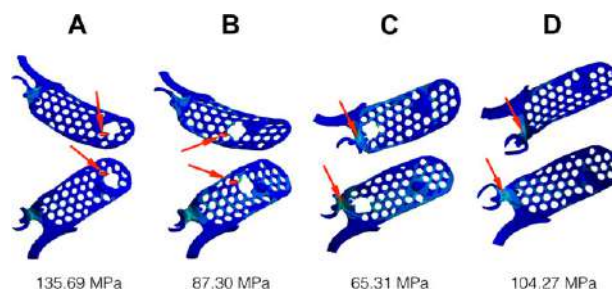


Figure 11 Von Mises stress map of metal structure (maximum values in red, minimum values in blue). Red arrow indicates location of maximum stress values.

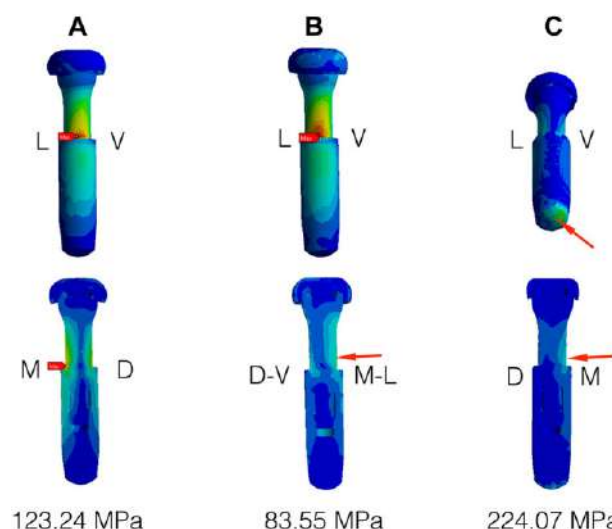


Figure 12 Von Mises stress map of implant, Locator® abutment, and metal retainer (maximum values in red, minimum values in blue). Mesial (M), distal (D), vestibular (V), and lingual (L) sides of implant are marked. Red arrow indicates location of maximum stress values.

were considered isotropic instead of orthotropic, where directions of forces are oriented in three different planes of space and represent a more realistic behavior of jaw bones.³⁰ Finally, a simple rotational movement of the model was used trying to simulate complex TMJ movements.

Although minimal differences were found, implant position had an impact on the biomechanical behavior of IAPRDPs; however, the methodology used in this study intended to be as close as possible to a real clinical scenario and updated to the new standards in implant dentistry by using a 3D model of a real patient's anatomy, nonlinear deformation of the PDL, use of internal conical connection implant system, and use of the Locator® attachment system. Such considerations have made comparisons with similar studies difficult.^{5,12,15,18,20} For instance, displacements and stress results obtained in two similar studies where implant location in IAPRDP was analyzed^{5,12} were different from those obtained in this study. One possible explanation would be that the magnitude and direction of masticatory forces were different, and also that the displacements of the different models during simulation were restrained at the

bottom of the mandible, whereas in our study, such restraint was located at the distal part of the model allowing a rotational movement. When analyzing results of the overall displacement values, they were slightly different from Cunha *et al*'s study,⁵ which showed general displacements of 0.117 mm placing the implant in the second molar, 0.107 mm placing the implant in the first molar, and 0.112 mm placing the implant in the second premolar; however, these results agree with those obtained in our study, that the maximum displacement reached was found in the control model, and the lowest in the model where the implant was placed in the area of the first molar, model B.

In general, no major differences were found between the test models in terms of maximum stress; however, differences were found between the test and control. Generally, in the control model, maximum stress was located in the biological structures such as the mandible, tooth, soft tissue, and PDL. Therefore, the incorporation of an implant in the PRDP resulted in a reduction of stress in these structures. This evidence was also found in other similar studies.^{5,12,14,15} Although the placement of the implant improves the stability of the denture and relieves stresses in biological structures, it also increases stress in non-living tissues such as the implants, metal framework, and resin of the PRDP.^{5,20}

The stress analysis of the mandible bone in our study, regardless of the position of the implant, was distributed similarly in all models; however, some differences could be seen between test models when analyzing the area of the peri-implant bone. In such areas, the implant in the first molar position offered a more favorable distribution and dissipation of stress along the entire length of the peri-implant bone (Fig 8B), compared with models A and C, where such stress was concentrated in the area of the prosthetic interface (Figs 8A and C). In Cunha *et al*'s study,⁵ the maximum stresses were higher than those found in our study, ranging from 17.46 to 22.93 MPa and all being located at the apex of the implant. In Memari *et al*'s study,¹² placing the implant in the first molar area presented the lowest stress value (4.1985 MPa) in the cortical bone. Such differences could be explained by the different location of the displacement strain, as mentioned earlier.

The stress found in the PDL was very similar in all our models (0.101 - 0.105 MPa). Stress was poorly distributed and highly localized in the lingual and mesial aspects of the PDL. Cunha *et al*⁵ found that the model with the implant in the premolar area reduced the stress values of the PDL, obtaining the lowest value of 10.772 MPa. In our study, when analyzing the nonlinear strain values some differences were seen between the test and the control models. The maximum strain was found in the control model (27%), and the minimum strain was found in model C, with the implant located in the second premolar (21%), reinforcing the idea that IAPRDP can reduce strain forces in the PDL, especially when such an implant is placed in the second premolar area.

With regard to the stress found in the metal framework of the PRDP, its distribution was very similar in all models, being concentrated at the base of the minor connectors, at the junction of the lingual bar connector and the resin base (Fig 11). In test models, stress was observed in the area surrounding the retentive part of the Locator[®] abutment (Figs 11A to C). In model C (implant in the premolar area) these two stress

concentration points were close together due to the proximity of the resilient attachment housing to the minor connector (Fig 11C), therefore increasing the concentration of stress in this area. This could explain how in some clinical cases where implants were placed in the premolar areas, the metal framework of the IAPRDP fractured.²⁹ Therefore, a correct design of the metal framework is recommended, especially when the implant is close to the remaining teeth.²⁹

Stress analyzed in the implants (Fig 12) was quite lower than those found in Cunha *et al*'s⁵ study model, being 297.61 MPa in the second molar implant, 283.18 MPa in the first molar implant, and 245.094 MPa in the implant at the level of the second premolar. In Cunha *et al*'s study, maximum stress values were located in the middle distal part of the internal connection area of the implant. In our study, maximum stress was located in the portion of the prosthetic connection of the implant, except in model C (Fig 12C), which obtained the highest stress, and these were located in the apical portion of the implant, probably due to its tilted position. In Memari *et al*'s¹² 3D study, the maximum implant stress values were 14.585 MPa in the implant placed in the second molar area and 16.02 MPa in the implant placed in premolar region. The lowest value was found in the first molar area and was 13.108 MPa. Although such results were significantly lower than the results obtained in our study, they agree that the implant in the first molar position obtained the lowest values and more favorable stress distribution along the length of the implant and the Locator[®] abutment (Fig 12B).

Although minimal differences in displacements and stress values were found between test models, they showed improved results compared with the control model, reinforcing the idea that placing an implant in the distal edentulous area would minimize the biomechanical limitations of a conventional PRDP.^{10,19,30-33} Moreover, model B (Fig 5B) obtained an improved biomechanical behavior, considering the general displacement values, maximum stress, and distribution in the peri-implant bone, metal framework, and implant. Despite the differences in methodology used, the same conclusion was also reached in Cunha *et al*'s⁵ and Memari *et al*'s¹² investigations, which also found this position to be the most appropriate in the treatment of IAPRDP.

Conclusions

Within the limitations of this *in vitro* study we can conclude the following:

1. Placement of an Ankylos implant with a Locator[®] abutment, independent of its position in the edentulous ridge, improved the biomechanical behavior of PRDP.
2. Placing the implant in the first molar area showed enhanced biomechanical results, when considering general displacements and maximum stress values and their distribution in peri-implant bone, PRDP metal framework, and implant.

Well-designed clinical studies are needed to validate such findings.

Acknowledgements

The FEA of this research work has been done at the technological center of Catalunya Eurecat, Cerdanyola del Vallés (Barcelona). The authors would like to give special thanks to the engineering supervisor Joaquim Gonzalez Vila.

References

- Keltjens HM, Kayser AF, Hertel R, et al: Distal extension removable partial dentures supported by implants and residual teeth: considerations and case reports. *Int J Oral Maxillofac Implants* 1993;8:208-213
- Kuzmanovic DV, Payne AGT, Purton DG: Distal implants to modify the Kennedy classification of a removable partial denture: a clinical report. *J Prosthet Dent* 2004;92:8-11
- Grossmann Y, Nissan J, Levin L: Clinical effectiveness of implant-supported removable partial dentures—a review of the literature and retrospective case evaluation. *J Oral Maxillofac Surg* 2009;67:1941-1946
- Ohkubo C, Kurihara D, Shimpō H, et al: Effect of implant support on distal extension removable partial dentures: in vitro assessment. *J Oral Rehabil* 2007;34:52-56
- Cunha LDAP, Pellizzer EP, Verri FR, et al: Evaluation of the influence of location of osseointegrated implants associated with mandibular removable partial dentures. *Implant Dent* 2008;17:278-287
- Turkylmaz I: Use of distal implants to support and increase retention of a removable partial denture: a case report. *J Can Dent Assoc* 2009;75:655-658
- Wismeijer D, Tawse-Smith A, Payne AGT: Multicentre prospective evaluation of implant-assisted mandibular bilateral distal extension removable partial dentures: Patient satisfaction. *Clin Oral Implants Res* 2013;24:20-27
- Mijiritsky E, Lorean A, Mazor Z, et al: Implant tooth-supported removable partial denture with at least 15-year long-term follow-up. *Clin Implant Dent Relat Res* 2015;17:917-922
- Ohkubo C, Kobayashi M, Suzuki Y, et al: Effect of implant support on distal-extension removable partial dentures: in vivo assessment. *Int J Oral Maxillofac Implants* 2008;23:1095-1101
- Shahmiri RA, Atieh MA: Mandibular Kennedy Class I implant-tooth-borne removable partial denture: a systematic review. *J Oral Rehabil* 2010;37:225-234
- Geng JP, Tan KB, Liu GR: Application of finite element analysis in implant dentistry: a review of the literature. *J Prosthet Dent* 2001;85:585-598
- Memari Y, Geramy A, Fayaz A, et al: Influence of implant position on stress distribution in implant-assisted distal extension removable partial dentures: a 3D finite element analysis. *J Dent* 2014;11:523-530
- Maeda Y, Sogo M, Tsutsumi S: Efficacy of a posterior implant support for extra shortened dental arches: a biomechanical model analysis. *J Oral Rehabil* 2005;32:656-660
- Verri FR, Pellizzer EP, Rocha EP, et al: Influence of length and diameter of implants associated with distal extension removable partial dentures. *Implant Dent* 2007;16:270-280
- Pellizzer EP, Verri FR, Falcón-Antenucci RM, et al: Evaluation of different retention systems on a distal extension removable partial denture associated with an osseointegrated implant. *J Craniofac Surg* 2010;21:727-734
- de Freitas Santos CM, Pellizzer EP, Verri FR, et al: Influence of implant inclination associated with mandibular class I removable partial denture. *J Craniofac Surg* 2011;22:663-668
- Cunha LDAP, Pellizzer EP, Verri FR, et al: Influence of ridge inclination and implant localization on the association of mandibular Kennedy class I removable partial denture. *J Craniofac Surg* 2011;22:871-875
- Shahmiri R, Aarts JM, Bennani V, et al: Finite element analysis of an implant-assisted removable partial denture. *J Prosthodont* 2013;22:550-555
- Shahmiri R, Aarts JM, Bennani V, et al: Strain distribution in a Kennedy class I implant assisted removable partial denture under various loading conditions. *Int J Dent* 2013;2013:351279
- Shahmiri R, Das R, Aarts JM, et al: Finite element analysis of an implant-assisted removable partial denture during bilateral loading: occlusal rests position. *J Prosthet Dent* 2014;112:1126-1133
- Schmitt CM, Nogueira-Filho G, Tenenbaum HC, et al: Performance of conical abutment (Morse Taper) connection implants: a systematic review. *J Bio Mat Res* 2014;102:552-574
- Schneider AL, Kurtzman GM: Bar overdentures utilizing the Locator attachment. *Gen Dent* 2001;49:210-214
- Chikunov I, Doan P, Vahidi F: Implant-retained partial overdenture with resilient attachments. *J Prosthodont* 2008;17:141-148
- Kanbara R, Nakamura Y, Ochiai KT, et al: Three-dimensional finite element stress analysis: the technique and methodology of non-linear property simulation and soft tissue loading behavior for different partial denture designs. *Dent Mater J* 2012;31:297-308
- DeTolla DH, Andreana S, Patra A, et al: Role of the finite element model in dental implants. *J Oral Implantol* 2000;26:77-81
- Ormianer Z, Palti A, Demiralp B, et al: Implant-supported first molar restorations: correlation of finite element analysis with clinical outcomes. *Int J Oral Maxillofac Implants* 2012;27:e1-12
- Morneburg TR, Pröschel PA: Measurement of masticatory forces and implant loads: a methodologic clinical study. *Int J Prosthodont* 1989;15:20-27
- Toms SR, Eberhardt AW: A nonlinear finite element analysis of the periodontal ligament under orthodontic tooth loading. *Am J Orthod Dentofac Orthop* 2003;123:657-665
- Verri FR, Cruz RS, de Souza Batista VE, et al: Can the modeling for simplification of a dental implant surface affect the accuracy of 3D finite element analysis? *Comput Methods Biomech Biomed Engin* 2016;19:1665-1672
- Korioth TW, Versluis A: Modeling the mechanical behavior of the jaws and their related structures by finite element (FE) analysis. *Crit Rev Oral Biol Med* 1997;8:90-104
- Ortiz-Puigpelat O, Gargallo-Albiol J, Hernandez-Alfaro F, et al: Short-term retrospective case series of implant-assisted removable partial dentures with locator abutments. *Int J Periodontics Restorative Dent* 2014;34:e121-128
- Mitrani R, Brudvik JS, Phillips KM: Posterior implants for distal extension removable prostheses: a retrospective study. *Int J Periodontics Restorative Dent* 2003;23:353-359
- Grossmann Y, Levin L, Sadan A: A retrospective case series of implants used to restore partially edentulous patients with implant-supported removable partial dentures: 31-month mean follow-up results. *Quintessence Int* 2008;39:665-671