Biomechanical behavior of atrophic maxillary restorations using the all-on-four concept and long trans-sinus implants: A finite element analysis

Liliane Pacheco de Carvalho¹, Alexandre Marcelo de Carvalho²*, Carlos Eduardo Francischone¹, Flavia Lucisano Botelho do Amaral³, Bruno Salles Sotto-Maior⁴

¹Department of Prosthodontics, Faculty of Dentistry UNIFAGOC Institute and Research Center, Brazil
²Department of Periodontology, Faculty of Dentistry UNIFAGOC Institute and Research Center, Brazil
³Department of Implantology, Faculty of Dentistry, Dental Research Center of São Leopoldo Mandic, Brazil
⁴Department of Restorative Dentistry, Faculty of Dentistry, Federal University of Juiz de Fora, Brazil

Abstract

Background. Maxillary bone atrophy with a considerable amount of pneumatization and anterior expansion of the maxillary sinus might be a situation limiting oral rehabilitation with osseointegrated implants. Therefore, the present study aimed to biomechanically evaluate two rehabilitation techniques for maxillary bone atrophy: all-on-four and long trans-sinus implants.

Methods. Two three-dimensional models consisting of atrophic maxilla with four implants were simulated. In the M1 model, two axially inserted anterior implants and two tilted implants, 15 mm in length, placed tangential to the maxillary sinus’s anterior wall were used. In the M2 model, two axially inserted anterior implants and two trans-sinus tilted implants, 24 mm in length, were used. For the finite element analysis (FEA), an axial load of 100 N was applied on the entire extension of the prosthesis, simulating a rehabilitation with immediate loading. The peri-implant bone and the infrastructure were analyzed according to the Mohr-Coulomb and Rankine criteria, respectively.

Results. The results were similar when the stresses on peri-implant bone were compared: 0.139 and 0.149 for models 1 and 2, respectively. The tension values were lower in the model with trans-sinus implants (27.99 MPa).

Conclusion. It was concluded that the two techniques exhibited similar biomechanical behavior, suggesting that the use of long trans-sinus implants could be a new option for atrophic maxilla rehabilitation.

Introduction

Based on the placement of only four implants for rehabilitating atrophic maxillae, the all-on-four concept has been used and associated with high success rates.¹ However, in some cases, bone remodeling in the posterior region of the maxilla is so severe that it should be extended to the anterior portion of the maxillary sinus, making it impossible to achieve implant anchorage in the region of the canine abutment, as recommended in the original technique for tilted implants.² In these situations, the alternatives for rehabilitation include maxillary sinus lift surgeries using autogenous, homogenous, heterogenous bone, or bone morphogenetic proteins. These techniques have been associated with varied morbidity, depending on the option selected, and demand a waiting time of 4–12 months for bone repair, making it unfeasible to place implants during the first stage of surgery.¹,⁴,⁵

Thus, the rehabilitation based on anchoring in the remaining bone is an option for the rehabilitation of atrophic jaws with equally high success rates.¹,⁰ The use of trans-sinus implants is a treatment option in these cases. The anchoring technique with trans-sinus implants consists of crossing the implant through the maxillary sinus after elevating the sinus membrane and stabilizing it in the anterior wall of the maxillary sinus or the wall of the nasal fossa.⁵,⁷ Therefore, the implants need to be longer, i.e., 18–24 mm in length.⁸ The present study aimed to compare the biomechanical performance of total edentulous rehabilitation, the all-on-four concept with tilted implants, and rehabilitation with the use of long trans-sinus implants, subjected to immediate loading in atrophic maxillae, using the finite element analysis (FEA). The null hypothesis indicated no biomechanical difference between the two rehabilitation techniques for edentulous maxilla, all-on-four and long trans-sinus implant concepts.

*Corresponding author: Alexandre Marcelo de Carvalho, Email: bruno.sotto@ufjf.edu.br

© 2021 The Author(s). This is an open access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.
Methods
Using computer-aided design software (SolidWorks 2019, SolidWorks Corporation), the bone models were constructed based on cone-beam computed tomography cross-sectional images of an edentulous atrophic human maxilla. The images were obtained from the database of the School of Dentistry of the Federal University of Juiz de Fora. The bone model consisted of medullary bone surrounded by cortical bone with an average thickness of 1 mm, with the aid of the InVesalius and SolidWorks 2019 software. A model of a complete maxillary prosthesis was scanned using a 3D laser scanner (Nextengine HD, Santa Monica, USA) to obtain the three-dimensional geometry of the prosthesis. The models were saved in STL format (Stereolithography, 3D Systems, Rock Hill, USA) for later processing in CAD type SolidWorks 2019 software (Dassault Systems, SolidWorks Corps, USA) to obtain the virtual model of the prosthesis with a metallic bar and dentogingival acrylic resin. The computed models of the implants and prosthetic components (Figure 1) were acquired from the manufacturer (SIN – Sistemas de Implantes Nacional, São Paulo, Brazil).

The models obtained from the tomograph and prosthesis were combined with the models of implants and components to represent a complete, fixed, implant-supported prosthesis with the following characteristics: model M1, simulating treatment according to the all-on-four technique; SW external hexagon implants with a platform 4.1 mm in diameter and a body 3.75 mm in diameter, 11 mm in length (SW HE 3711 SIN – Sistema de Implante Nacional- São Paulo, Brazil) for the anterior implants, and tilted implants 15 mm in length in the posterior region, tangential to the anterior wall of the maxillary sinus (SWHE 3715-SIN – Sistema de Implante Nacional- São Paulo, Brazil) were used. For model M2, simulating treatment with long trans-sinus implants, 11-mm-long anterior implants were placed axially; parallel and tilted implants placed in the posterior region were anchored in the remaining alveolar bone, passing parallel and tilted implants placed in the posterior region, perpendicular to the occlusal plane, applied throughout the entire extent of the prosthesis, simulating immediate loading. The ANSYS® software was used to calculate the values of von Mises stress for cortical and trabecular bone, implants, and prosthetic framework.

Results
Distinct criteria were used to analyze the different materials in the present study due to each material’s inherent characteristics and behavior. The peri-implant bone was analyzed according to the Mohr-Coulomb criterion. Figures 3 and 4 present the results. The prosthesis infrastructure was analyzed according to the Rankine criterion. Figures 5 and 6 present the results.

Discussion
Rehabilitation of the atrophic maxilla with the all-on-four concept has been established in the literature. The use of trans-sinus implants has also previously been reported by other authors; however, other authors have

| Component               | Young’s modulus (E) (MPa) | Shear modulus (G) (MPa) | Poisson ratio (δ) |
|-------------------------|---------------------------|-------------------------|-------------------|
| Cortical bone           | Ex 12600                  | Ez 19400                | δxz 0.3           |
|                         | Ey 12600                  | Gyz 5700                | δyz 0.39          |
|                         | Ez 19400                  | Gxz 5700                | δxz 0.39          |
| Trabecular bone         | Ex 1150                   | Gox 6800                | δxz 0.001         |
|                         | Ey 2100                   | Gyz 4340                | δyz 0.32          |
|                         | Ez 1150                   | Gxz 6800                | δxz 0.05          |
| Titanium (implant and abutments) | 104000                   | 38800                   | 0.34              |
| Acrilic                 | 1960                      | 24                      | 0.35              |

Table 1. Material attributed to each region of the model and properties of the materials.
used conventional implants up to 15-mm long.\textsuperscript{6,7,12,13} The particularity of the present technique lies in the use of extra-long trans-sinus implants up to 24 mm, described in 2017.\textsuperscript{8} However, biomechanical analyses of these rehabilitations are still inadequate in the literature, a factor that prompted the present study.

Given the results, very close stresses on the peri-implant tissues were observed in the two models, with a discrete rise in values in the model with trans-sinus implants. This might be explained by the greater inclination of trans-sinus implants relative to the bone crest, favoring the accumulation of stresses in the peri-implant bone region compared with the all-on-four model. Another fact to consider is the changes in bone insertion. Let us consider the site prepared for the insertion of these implants. It is composed of two anchorage units, with one being represented by the low density and volume and the other by the greater volume and density during a masticatory effort in immediate loading. When a load is applied, there is a tendency to form a gap between the implant and bone of the remaining alveolar ridge, and since it is not yet osseointegrated, the implant tends to undergo slight micromovements within the bone. However, the values obtained in both models were within the acceptable limits for rehabilitation with immediate loading.\textsuperscript{14,15}

The present study recommends long implants because they can be inserted in a trans-sinus manner, with apical anchorage on the canine abutment. In addition, this allows a more posterior positioning of its platform. Given the prostheses structure results, a considerable reduction in stress peaks was verified in the model with long trans-sinus implants. This suggested that the emergence of these implants in a posterior position eliminates the extension in the cantilever of the prosthesis, and therefore, increases the polygon of its support, indicating a better mechanical performance of this model. This corroborates the findings of Silva et al.,\textsuperscript{14} who observed that the cantilever significantly increased the stress levels on the implant-prosthesis set.

Another fact to consider is that long implants allowed cortical bone insertion in the region of the canine\textsuperscript{15-18} abutment with greater bone density. This is an important condition for primary stability and can give rise to a more favorable distribution of stresses on the prosthesis infrastructure, which could be a decisive factor in the treatment’s longevity. This characteristic overlaps the technique recommended by Malo, in which the implants are tangential to the anterior wall of the sinus and are not considered trans-sinus. Thus, they are only feasible when there is a large volume of remaining alveolar bone.
with rates that suggest success.

Authors’ Contributions
LPDC initiated, conceptualized, and supervised the research work. AMDC, CEF, and FLBDA prepared samples and performed the study with the collaboration of LPDC, BSSW, and CEF. All authors have contributed to analyzing the data and writing the manuscript.

Acknowledgments
The authors would like to thank the UNIFAGOC Institute and Research Center, Brazil, for the authorization of this research.

Funding
The work has no funding.

Competing Interests
We declare no conflict of interests.

Ethics Approval
Not applicable

References
1. Maló P, de Araújo Nobre M, Lopes A, Ferro A, Botto J. The All-on-4 treatment concept for the rehabilitation of the completely edentulous mandible: a longitudinal study with 10 to 18 years of follow-up. Clin Implant Dent Relat Res. 2019;21(4):565-77. doi: 10.1111/cid.12769.
2. Maló P, Araújo Nobre MD, Lopes A, Rodrigues R. Double full-arch versus single full-arch, four implant-supported rehabilitations: a retrospective, 5-year cohort study. J Prosthodont. 2015;24(4):263-70. doi: 10.1111/jopr.12228.
3. Francetti L, Rodolfi A, Barbaro B, Taschieri S, Cavalli N, Corbella S. Implant success rates in full-arch rehabilitations supported by upright and tilted implants: a retrospective investigation with up to five years of follow-up. J Periodontal Implant Sci. 2015;45(6):210-5. doi: 10.3051/jpis.2015.45.6.210.
4. Fortin Y, Sullivan RM. Terminal posterior tilted implants planned as a sinus graft alternative for fixed full-arch implant-supported maxillary restoration: a case series with 10- to 19-year results on 44 consecutive patients presenting for routine maintenance. Clin Implant Dent Relat Res. 2017;19(1):56-68. doi: 10.1111/cid.12433.
5. Bhering CL, Mesquita MF, Kemmoku DT, Noritomi PY, Consani RL, Barão VA. Comparison between all-on-four and all-on-six treatment concepts and framework material on stress distribution in atrophic maxilla: a prototyping guided 3D-FEA study. Mater Sci Eng C Mater Biol Appl. 2016;69:715-25. doi: 10.1016/j.msec.2016.07.059.
6. Jensen OT, Cottam J, Ringeman J, Adams M. Trans-sinus dental implants, bone morphogenetic protein 2, and immediate function for all-on-4 treatment of severe maxillary atrophy. J Oral Maxillofac Surg. 2012;70(1):141-8. doi: 10.1016/j.oms.2012.03.045.
7. de Carvalho AM, de Carvalho LP, de Lima Romeiro R, Francischone CE, Sotto-Maior BS, Bezerra F. Nova Proposta Para Reabilitação de Maxila Atrófica: Implante Inclinado Longo. Int J Oral Maxillofac Implants. 2016;31:1017-22.
8. Vasco MA, de Souza J, de Las Casas EB, de Castro e Silva AL, Hecke M. A method for constructing teeth and maxillary bone parametric model from clinical CT scans. Comput Methods Biomech Biomed Eng Imaging Vis. 2015;3(3):117-22. doi: 10.1080/21681163.2014.899579.
9. Crespi R, Vinci R, Capparé P, Romanos GE, Gherlone E. A clinical study of edentulous patients rehabilitated according to the “all on four” immediate function protocol. Int J Oral Maxillofac Implants. 2012;27(2):428-34.
10. Balshi TJ, Wolfinger GJ, Slauch RW, Balshi SF. A retrospective...
analysis of 800 Brånemark system implants following the All-on-Four™ protocol. J Prosthodont. 2014;23(2):83-8. doi: 10.1111/jopr.12089.

11. Testori T, Mandelli F, Mantovani M, Taschieri S, Weinstein RL, Del Fabbro M. Tilted trans-sinus implants for the treatment of maxillary atrophy: case series of 35 consecutive patients. J Oral Maxillofac Surg. 2013;71(7):1187-94. doi: 10.1016/j.joms.2013.02.013.

12. Maló P, de Araújo Nobre M, Lopes A, Rodrigues R. Preliminary report on the outcome of tilted implants with longer lengths (20-25 mm) in low-density bone: one-year follow-up of a prospective cohort study. Clin Implant Dent Relat Res. 2015;17 Suppl 1:e134-42. doi: 10.1111/cid.12144.

13. Maló P, Nobre M, Lopes A. Immediate loading of ‘All-on-4’ maxillary prostheses using trans-sinus tilted implants without sinus bone grafting: a retrospective study reporting the 3-year outcome. Eur J Oral Implantol. 2013;6(3):273-83.

14. Silva GC, Mendonça JA, Lopes LR, Landre Jr J. Stress patterns on implants in prostheses supported by four or six implants: a three-dimensional finite element analysis. Int J Oral Maxillofac Implants. 2010;xz25(2):239-46.

15. Zétola AL, Verbicaro T, Littieri S, Larson R, Giovannini AF, Deliberador TM. Recombinant human bone morphogenetic protein type 2 in the reconstruction of atrophic maxilla: Case report with long-term follow-up. J Indian Soc Periodontol. 2014;18(6):781-5. doi: 10.4103/0972-124x.147437.

16. Esposito M, Barausse C, Pistilli R, Sammartino G, Grandi G, Felice P. Short implants versus bone augmentation for placing longer implants in atrophic maxillae: one-year post-loading results of a pilot randomised controlled trial. Eur J Oral Implantol. 2015;8(3):257-68.

17. Falah M, Srouji S. A discussion concerning direct bone regeneration on and around inserted dental implants in maxillary sinus lifting procedures without any placement of bony substitutes. Int J Oral Maxillofac Surg. 2015;44(12):1582-3. doi: 10.1016/j.ijom.2015.08.990.

18. Asawa N, Bulbulen N, Kakade D, Shah R. Angulated implants: an alternative to bone augmentation and sinus lift procedure: systematic review. J Clin Diagn Res. 2015;9(3):ZE10-3. doi: 10.7860/jcdr/2015/11368.5653.

19. Cannizzaro G, Felice P, Buti J, Leone M, Ferri V, Esposito M. Immediate loading of fixed cross-arc prostheses supported by flapless-placed supershort or long implants: 1-year results from a randomised controlled trial. Eur J Oral Implantol. 2015;8(1):27-36.

20. Menini M, Pesce P, Bevilacqua M, Pera F, Tealdo T, Barberis F, et al. Effect of framework in an implant-supported full-arch fixed prosthesis: 3D finite element analysis. Int J Prosthodont. 2015;28(6):627-30. doi: 10.11607/ijp.4345.

21. Grandi T, Faustini F, Casotto F, Samarani R, Svezia L, Radano P. Immediate fixed rehabilitation of severe maxillary atrophies using trans-sinus tilted implants with or without sinus bone grafting: one-year results from a randomised controlled trial. Int J Oral Implantol (Berl). 2019;12(2):141-52.