

Original Article

Evaluation of stress distribution of porous tantalum and solid titanium implant-assisted overdenture in the mandible: A finite element study

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ABSTRACT

Aims: The present study aimed to evaluate the stress distribution of porous tantalum implant and titanium solid implant assisted overdenture (IAO) in mandibular bone by utilizing three-dimensional (3D) finite element (FE) analysis.

Materials and Methods: In this FE study, an existing cone-beam volumetric tomography scan of a patient without any maxillofacial anomaly with an available acceptable IAO for mandible was used to attain the compartments of a completely edentulous mandible. Zimmer trabecular implants and locator attachment systems were selected as the case group (Model B), and Zimmer Screw-Vent implants and locator attachment system were chosen for the control (Model A), as overdenture attachments in the present study. The mandibular overdenture was scanned and digitized as a FE model. Two 3D FE models were designed as edentulous lower jaws, each with four implants in the anterior section of the mandible. Three forms of loads were directed to the IAO in each model: Vertical loads on the left first molar vertical molar (VM). Vertical loads on the lower incisors (VI). Inclined force buccolingually applied at left first molar (IM).

Results: Under all loading conditions, the maximum strain values in peri-implant bone in Model A were less than Model B. Under VI, the greatest stress value around abutments in both models was about 2–3 times higher than the other loads. Under VM and IM loads, no significant difference was observed between models.

Conclusion: Using trabecular metal implants instead of solid implants reduces strain values around both cortical and trabecular bone.

Key Words: Dental implants, overdenture, porous, tantalum

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INTRODUCTION

Edentulous patients with mandibular bone resorption deal with the problem of adjustment to mastication and report disappointment with their conventional full dentures regularly.^[1] Implant-assisted overdenture (IAO) is considered as one of these treatment options which can enhance prosthesis

performance and patient's satisfaction and are implied when patients are dissatisfied with the stability and retention of their complete denture.^[2,3] The use of dental implants can offer alternative ways to improve the quality of the treatment for these patients.^[2] The problems with mandibular complete dentures

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deteriorate with the constant resorption of the residual bone.^[4] However, osseointegrated implants slow down bone reduction in the zone.^[5] In addition, the implant survival rate in IAO is not related to age, sex, and splinting, but the long-term results suggest that the number of implants can change the survival rate.^[6] Further, the success of implants relies on various factors such as basic characteristics of the implant itself including design, substance, and fabrication process.^[7] Regarding the design features, the general conformation of the implant affects the pattern of stress distribution into the surrounding bone, following its long-term success or failure.^[7] Bite strokes applied to dental implants can generate excessive stress in peripherals bone, which may lead to bone defects and consequent failure of implants.^[8] Therefore, it is essential to evaluate the quality and magnitude of these forces on implants and in the bone to explain the *in vivo* performance of these devices.^[9]

Nowadays, locator attachments have received a lot of attention, due to its self-alignment, satisfactory retention, and minimum height requirements. In addition, nonsplinting implant is necessary for locator attachment system and is shown to provide superior retention, compared to other stud attachments for overdentures, which can address an increased load to the implants.^[10,11] Locator system shows higher service repetition due to nylon high rate of distortion and deterioration. Therefore, the main problem for the locator system is related to its need for replacement in a reduced time frame, compared to other retentive systems.^[11]

Recently, dental implants have been introduced with porous tantalum parts.^[12] Porous tantalum metal is utilized to enhance the contact between bone and dental implants.^[13] In theory, this type of implant is more advantageous compared to standard titanium implants. For example, its elastic modulus (1.3–10 GPa) is more similar to that of cortical (12–18 GPa) and cancellous bone (0.1–0.5 GPa) is used in the structure of dental implants such as titanium and titanium alloy, compared to the most common materials (106–115 GPa), leading to a decrease in the stress shielding effects, which helps to preserve bone mineral density around implants.^[12] As reported in the study review conducted by Liu *et al.*, porous tantalum presents a favorable operation potential to enhance the clinical function of dental implants.^[12]

Hypothetically, this porous tantalum trabecular metal™ added to conventional titanium implants may function

as a helpful choice for patients with a less dense bone.^[14] The porous tantalum part of the implant permits rapid endothelial growth and proliferation through the trabecular structure, which is critical to allow for osteoblast precursor enrollment, osteoblastic cell differentiation, and matrix secretion.^[15] Lee *et al.* placed conventional solid titanium and porous tantalum implants bilaterally into mandibular extraction sockets in dogs, and the results indicated no significant difference between implant stability in two groups.^[16] Interim results of a 3-year study on immediate loading of reticular tantalum implants presented a 100% survival rate after 1 year of clinical follow-up.^[17]

Finite element analysis (FEA) is considered a method for finding a solution to a multifaceted mechanical problem by separating the problem domain into a pool of more modest domains.^[18] Such a structural analysis permits the visualization of stress and strain subsequent from an external force, load, thermal alternation, and other factors.^[19] Due to the large complicacy of the conformation of the implant-bone structure, FEA is presented as the most suitable tool for studying this system.^[18]

The application of porous tantalum implants has been emphasized due to the benefits of IAO in edentulous patients, as well as the problems and challenges related to the success of titanium implants for treating patients with poor bone quality. However, the data are not enough regarding the behavior and function of these implants. Thus, further studies should be conducted for a better understanding of the mechanical properties among these types of implants. Therefore, the present study aimed to evaluate the stress distribution of tantalum porous implant and titanium solid IAO in mandibular bone by utilizing three-dimensional (3D) FEA.

MATERIALS AND METHODS

Model design

In this FE study, an existing cone-beam volumetric tomography (CBVT) scan of a patient without any maxillofacial anomaly and average craniofacial proportions with an available acceptable IAO for mandible was used to attain the compartments of a completely edentulous mandible. Then, the CBVT scanning files were imported into Mimics10.0 (Materialise, Leuven, Belgium).^[20]

Zimmer trabecular implants (Zimmer Dental trabecular metal implant, TMM4B10, 4.1 mm × 10 mm,

Zimmer Dental, Carlsbad, USA) and locator attachment systems (LOCATOR abutment, TLOC3/4, 3.5 mm × 4.1 mm, Zimmer Dental, Carlsbad, USA) were selected as the case group, and Zimmer Screw-Vent implants (Zimmer tapered Screw-Vent implant, TSVM4B10, 4.1 mm × 10 mm, Zimmer Dental, Carlsbad, USA) and locator attachment system (LOCATOR abutment, TLOC3/4, 3.5 mm × 4.1 mm, Zimmer Dental, Carlsbad, USA) were chosen for the control, as overdenture attachments in the present study. The size of the implants and their attachments for both models was 4.1 mm × 10 mm and 3.5 mm × 4.1 mm (width × length), respectively.^[20] The reticular part of the porous tantalum implant was designed as a 0.75-mm-thick layer with 4.5 mm height starting 2 mm apart from the implant bottom. This layer was supposed to be isotropic and homogenous such as the cancellous bone. The elastic modulus of the porous tantalum layer was considered as 3000 MPa average, regarding the Zimmer trabecular metal TM manufacturing process which is chemical vapor infiltration-chemical vapor deposition.^[12]

The implant-abutment complex was digitized using the Optical digitizing system ATOS II (GOM, Braun-Schweig, Germany). The mandibular overdenture was scanned and modeled as a wax rim with a denture base omitting the teeth to make the FE model simpler, as the 3D geometries of the lower jaw bone and prosthetic units were modeled in SolidWorks 2015 (Solidworks Corporation, MA, USA).^[20-22]

In addition, Abaqus 6.9 (Dassault Systems Simulia Corp, Providence, RI, USA) was used to mesh the structures of the lower jaw, overdenture, implant, and locator systems. Two 3D FE models were designed as edentulous lower jaws, each with four implants in the anterior section of the mandible in the interforaminal region to retain an overdenture. The implants were vertically placed and distributed between mental foramina at least 5 mm mesial to the mental foramen, and 10 mm distance to each other.^[20-23] To conduct the study, two models were used. The overdenture is assisted by four porous tantalum implants in Model A, whereas the overdenture was supported by four titanium implants in Model B.

The models were meshed with 3D four-node tetrahedron elements. The overall numbers of elements and nodes in Model A are 192,409 and 272,478, and in Model B are 170,470 and 242,201,

respectively [Table 1]. A refined mesh was generated in the inter foraminal region to reproduce the complex strain distribution observed in the peri-implant bone^[20] [Figure 1].

Material characteristics

The edentulous jaw was united a 2 mm continuous cortical bone layer around a cancellous bone core with D2 (Hounsfield number of 850–1250) density, covered by a 1 mm-thick mucosa. The locator attachment system included abutment, nylon replacement male, and titanium cap. The abutment and cap were made of Ti6Al4V titanium alloy, as it is the case for the implant. The material properties of the cortical and cancellous bone, mucosa, and prosthetic units were determined from the amounts obtained from the literature [Table 2]. All materials were assumed to be isotropic, homogeneous, and linearly elastic.^[12,24-28]

Contact management

Implants were considered entirely as osseointegrated. Thus, a mechanically flawless boundary was supposed to be between implant and bone. However, the boundary between the overdenture and the mucosa was not immobile while functioning. Instead, the overdenture was able to rotate and slide on the mucosa in various directions. To mimic this dislodgment, we assumed that sliding friction existed between the

Table 1: Total number of elements and nodes

	Elements	Nodes
Model A	192,409	272,478
Model B	170,470	242,201

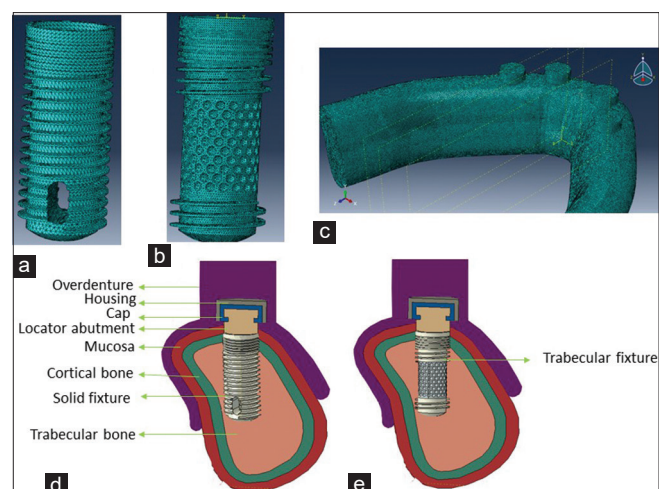


Figure 1: (a) solid fixture; (b) trabecular fixture; (c) fixtures inserted in mandibular bone; (d and e) finite element models of locator attachment overdenture supported by solid and trabecular metal implant.

overdenture and mucosa. The coefficient of sliding friction between the overdenture and mucosa was set as 0.334. The models were restrained at the nodes on the mesial and distal bone in all degrees of freedom.^[20] In addition, the interfaces between other parts including the locator attachment system, implant, and overdenture were set as fixed.^[20]

Loading conditions

Three forms of load were directed to the overdenture in each model to mimic functional loading as follows:

1. 100 N vertical loads on the left first molar (VM)^[2]
2. 100 N vertical loads on the lower incisors (VI)
3. 100 N, 45° angled force buccolingually applied at the center of the left first molar (IM).^[20]

RESULTS

Strain distribution in peri-implant cortical bone

Table 3 indicates the maximum strain in the cortical and trabecular bone around the implants in each model subjected to three forms of load. Figures 1-3 illustrate the strain distribution in the peri-implant cortical and trabecular bone in each model subjected to three loading conditions. Under all loading conditions, the maximum strain values in both cortical and trabecular bone were <2500 μ in each model, except for cortical bone under IM load. In both models, the peak strain values in the cortical and trabecular bone under IM load were higher than those in the other loads. Further, the maximum strain values in the peri-implant bone around trabecular metal implants were less than the solid implants under all

three loading conditions [Figures 2-4]. When models were loaded on the incisors, the peak strain values in the cortical bone concentrated around two mesial implants [Figure 2]. In both models, the maximum strain values in the cortical and trabecular bone under VM and IM loads concentrated on the distal side of the distal implant [Figures 3 and 4].

Stress in abutments

The maximum stress values in the abutments subjected to three loading conditions in each model are shown in Table 4. As shown, the greatest stress value in both models was about 2–3 times higher than the other loads under VI and was positioned on the labial aspect of the border between the abutment and the nylon replacement. Under all load conditions, maximum stress values on model B abutments were significantly less than Model A abutments.

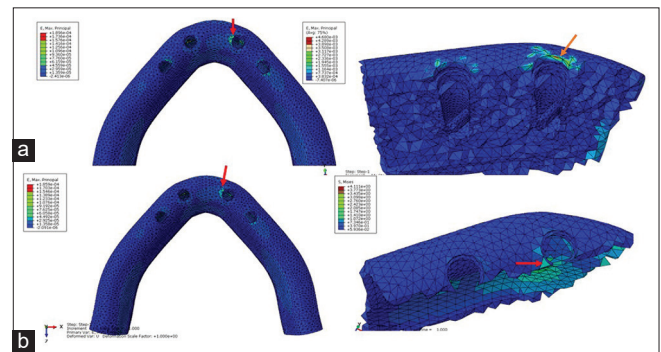


Figure 2: Strain distribution in the bone under VI loading condition. (a) Model A; (b) Model B. Colors indicate the level of strain from dark blue (lowest) to red (highest). The arrows show the sites with peak strain values.

Table 2: Material properties

Materials	Young's modulus (MPa)	Poisson ratio	References
Trabecular bone (D2)	1370	0.30	[24]
Cortical bone	13,700	0.30	[25]
Ti-6Al-4V	103,400	0.35	[26]
Nylon	28.3	0.4	Manufacturer
Mucosa	1	0.35	[27]
Overdenture	45,000	0.35	[28]
Porous tantalum (CVI/CVP)	3000 (2500-3500)	0.3	[12]

CVI: Chemical vapor infiltration; CVP: Chemical vapor deposition

Table 3: Maximum strains in the peri-implant bone under three loading conditions ($\mu\epsilon$)

Loading condition	VI		VM		IM	
	Cortical bone	Trabecular bone	Cortical bone	Trabecular bone	Cortical bone	Trabecular bone
Solid implant	1896	1187	1610	1090	2900	1523
Trabecular implant	1800	1064	1142	910	2720	1299

VM: Vertical loads on the left first molar; VI: Vertical loads on the lower incisors; IM: Inclined force buccolingually applied at left first molar

Pressure on the mucosa

Table 5 indicate the maximum pressure on mucosa under three loading conditions in each model. In both models, the maximum pressure on the mucosa under IM load was greater than that of other loads. The peak pressure in IM load was approximately three times higher than the VM load and was concentrated between the lateral side of the posterior alveolar ridge and the denture [Figures 5 and 6].

Under VM and IM loads, no significant difference was observed between models, but the pressure on the mucosa was higher in Model B under VI load.

DISCUSSION

The present study aimed to decide on the ideal implant design to support an overdenture in various loading conditions. Based on the results, the loading site was the most important parameter affecting the stress distribution in the whole system. Further, the inclined load on molar teeth induced higher stress levels on the cortical bone around the closest implant to the load site in both models, while vertical loads on the first molar tooth produced the lowest stress. Liu *et al.* and Chang *et al.* reported similar results in their studies.^[20-29]

The FEA result biologically revealed acceptable strain values in the bone surrounding the implants subjected to VI and VM loading conditions given that the mentioned value is below the biological resistance limits of bone, which is 2500 $\mu\epsilon$. However, when the models were subjected to IM loading conditions, a pathologic strain value around cortical bone was evident which may cause micromovements at the bone-implant interface, leading to the occurrence of

marginal bone loss. Jingyin *et al.* reported that the maximum strain value in the peri-implant bone under IM loading conditions was lower than 2500 $\mu\epsilon$. This controversy is probably caused by different jaw model designs and its effect on implant position.^[20] Further, changing the implant type to trabecular metal implant reduces the strain rate around both cortical and trabecular bone, especially under VM loading. Hence, it is recommended to use the trabecular implant to enhance IAOs success and survival rate by reducing marginal bone loss.

Assessing the maximum stresses on the cortical and cancellous bone units revealed that greatest von Mises stresses on the cortical bone segments were much higher than the von Mises stresses on the cancellous bone segment. It means that the cortical bone segment provides superior support for the implant than the trabecular segment. Due to the tight contact between

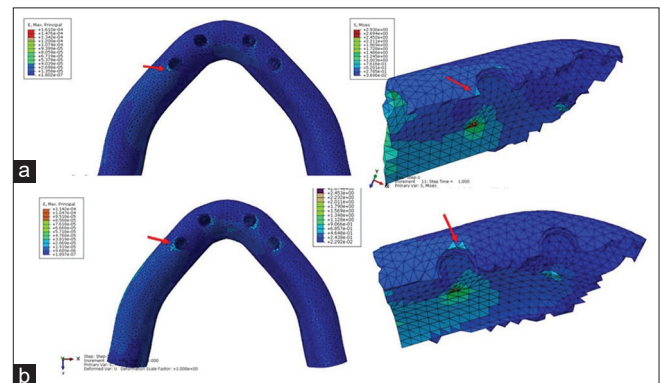


Figure 3: Strain distribution in the cortical bone under VM loading condition. (a) Model A; (b) Model B. Colors indicate the level of strain from dark blue (lowest) to red (highest). The arrows show the sites with peak strain values.

Table 4: Maximum stresses in abutments under three loading conditions (MPa)

Loading condition	VI	VM	IM
Solid implant	21.98	8.20	11.58
Trabecular implant	14.91	7.12	9.95

VM: Vertical loads on the left first molar; VI: Vertical loads on the lower incisors; IM: Inclined force buccolingually applied at left first molar

Table 5: Maximum pressure on mucosa under three loading conditions (MPa)

Loading condition	VI	VM	IM
Solid implant	0.487	0.227	0.687
Trabecular implant	0.554	0.227	0.678

VM: Vertical loads on the left first molar; VI: Vertical loads on the lower incisors; IM: Inclined force buccolingually applied at left first molar

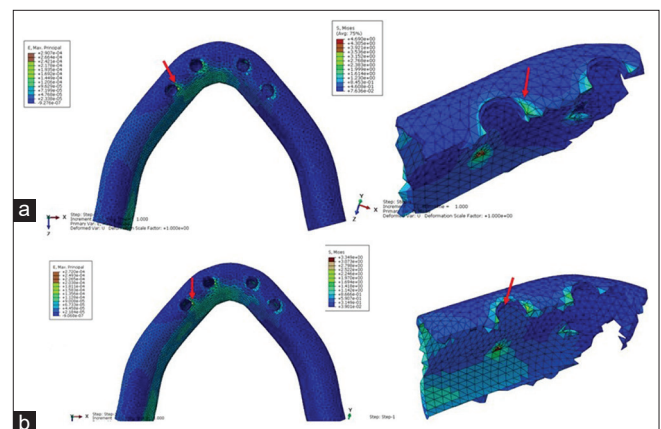


Figure 4: Strain distribution in the cortical bone under IM loading condition. (a) Model A; (b) Model B. Colors indicate the level of strain from dark blue (lowest) to red (highest). The arrows show the sites with peak strain values.

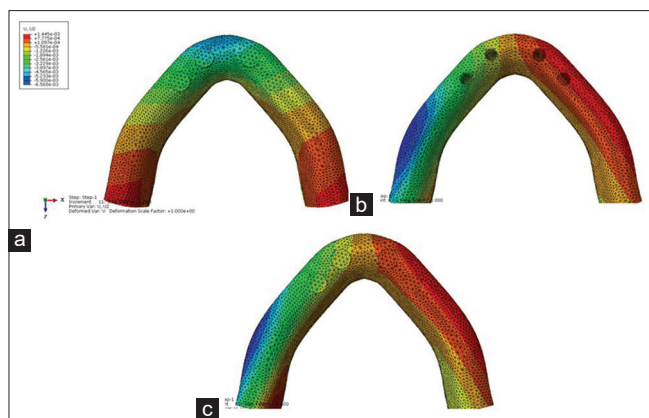


Figure 5: Pressure distribution on the mucosa of Model A under a VI (a), VM (b), IM (c) load (the cold tone describes the area where contact with the denture was close and tight, while the warm tone presents the area where the denture is tilted and detached from the mucosa).

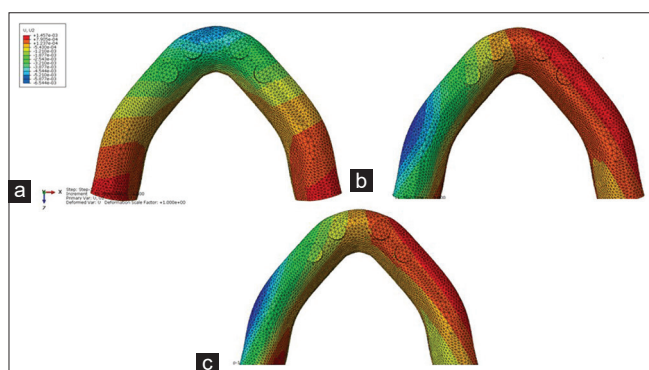


Figure 6: Pressure distribution on the mucosa of Model B under the VI (a), VM (b), IM (c) load (the cold tone describes the area where contact with the denture was close and tight, while the warm tone presents the area where the denture tilted and separated from the mucosa).

the cortical bone and implant, the loading applied to the implant is mostly transmitted into the thin cortical bone layer, which explains the clinical marginal bone loss around the implants. However, the results of the present study indicated that trabecular implants can help a better stress distribution between cortical and trabecular bone and can be a promising alternative for improved implant survival rate due to their low elastic modulus.

As described in the study of Topkaya and Solmaz, the stresses in the bone around the implants were found to be higher than the stresses measured on the jawbone. This could be explained by the high elastic modulus of the Ti6Al4V implant material, compared to the cortical and trabecular bone, which may decrease the elastic modulus of the trabecular metal implants leading to better stress distribution at the implant periphery.^[21]

In addition, under VI, which simulated the act of cutting food with anterior teeth, the largest stress value in the abutments in both models was 2–3 times higher than those in the other three models, indicating that possible damage to the abutments may happen more easily subjected to VI load.^[20] In this study, a significant reduction of stress was observed on the abutments connected to trabecular implants compared to the abutments connected to solid implants, leading to lesser maintenance frequency and prolonged abutment complex service life. The results of VI stress values in the study of Liu *et al.* are consistent with those in the present study, although it was higher under IM and VM load, which may be related to the result of differences in overdenture design and implant position between two the studies.^[20]

In previous studies, the boundary between the denture and the mucosa was supposed to be immobile for simplifying modeling and computations.^[30] However, in the present study, it was assumed that sliding friction is available between the denture and the mucosa. Further, the model of overdenture in this study could rotate and glide on the mucosa in different directions when functioning, which resulted in mimicking actual denture movements in regular use more precisely. Further, the results of the present study indicated that the contralateral side may bear less stress values than the loaded side when the model is subjected to posterior loads.^[20]

Based on the results, the largest pressure on the mucosa was recorded under IM loading conditions at the lateral side of the posterior region in both models. The second maximum pressure on the mucosa occurred under VI loading, due to the rotation of overdenture on the labial aspect of the mandibular ridge. In this regard, the results are in line with the study of Liu *et al.* Except for VI load, the change in the implant type made no difference in pressure on the mucosa. The largest pressure on mucosa under VI load was higher in Model B.

The FE models designed for the present study allows for representing a more comprehensive and complex geometry. On the other hand, the innate limitations of the FEA considering strain distribution should be highlighted.^[20] The used models were different from a clinical state in many aspects. All of the constructions in the models were supposed to be homogeneous, isotropic, and linearly elastic although the cortical bone of the mandible is a transversely isotropic and

inhomogeneous material. Further, a 100% implant/bone contact was created, which is inconsistent with clinical circumstances. Therefore, the FEA results of such conditions should be explained more meticulously. The certain values of different strains obtained in the present study are of little importance, whereas the relative values of different strains for different implant designs and load conditions are considered as the most important parts. Therefore, it is recommended to implement the results of this study as a reference to choose between different implant designs in the clinical treatment. Future clinical studies are essential for confirming the results.

CONCLUSION

Based on the results, the following conclusions were made:

- First, applying trabecular metal implant instead of solid implants reduced strain values around the both cortical and trabecular bone
- Second, IM load-induced greater stress values in peri-implant bone in both models
- Third, stress concentration on locator attached to reticular implant was significantly less than locator attachment on solid implants.

Finally, no significant difference was observed in pressure on the mucosa between trabecular and solid implants.

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Conflicts of interest

The authors of this manuscript declare that they have no conflicts of interest, real or perceived, financial or non-financial in this article.

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