Effect of insertion angle on the stability of orthodontic mini-implants in a rabbit tibia model: A finite element analysis

Efecto del ángulo de inserción en la estabilidad de miniimplantes ortodóncicos en un modelo de tibia de conejo: Modelo de elementos finitos

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Abstract

Introduction: *Mini-implants are an alternative to traditional methods of anchorage in orthodontic treatment. However, there are still questions concerning their application, in particular, with the insertion angle.* **Objective:** *To determine whether the angle of insertion of the mini-implant is a determining factor in their primary stability when they support orthodontic loads.* **Materials and Methods:** *A finite element model (FEM) of tibia bone, spring and mini-implant was developed. The three-dimensional model of the rabbit tibia was constructed based on tomographic slices. The angles that were analyzed were 90°, 80°, 70°, 60°, 50°, 45°, 40°, and 30°. A horizontal force of 2 N applied to the head of the mini-implants was simulated. The von Mises stresses and displacements were determined using FEM.* **Results:** *Von Mises stresses were lower for an insertion angle of 40° followed by 90° and 70°; likewise, the displacements of the mini-implants with respect to the spring were lower for the 40° angle followed by 90° and 70°, we found a statistically significant association between the insertion angle and displacement.* **Conclusion:** *All mini-implants underwent a degree of angulation and displacement; however, mini-implants inserted to the bone surface at 40° tend to have better primary stability, and they can withstand loads immediately.*

KEY WORDS: *Mini-implants. Orthodontics. Insertion angle. Finite element analysis. Biomechanics.*

Resumen

Introducción: *Los miniimplantes son una alternativa para los métodos de anclaje tradicionales en el tratamiento de ortodoncia. Sin embargo, existen interrogantes referentes a su uso, en particular en cuanto al ángulo de inserción.* **Objetivo:** *Determinar si el ángulo de inserción es un factor determinante en la estabilidad primaria de los miniimplantes cuando soportan cargas.* **Método:** *Se desarrolló un modelo tridimensional de elementos finitos del conjunto tibia, miniimplante y resorte a partir de cortes tomográficos; finalmente, el resorte fue modelado empleando elementos de contacto. Las angulaciones analizadas fueron 90°, 80°, 70°, 60°, 50°, 45°, 40° y 30°. Una fuerza de 2 N fue aplicada a los implantes. Se determinaron los esfuerzos de von Mises y los desplazamientos empleando elementos finitos.* **Resultados:** *Los esfuerzos de von Mises fueron menores para un ángulo de inserción de 40°, seguido por los de 90° y 70°; de igual forma, los desplazamientos en los miniimplantes con respecto al resorte fueron menores para un ángulo de 40°, seguido por los de 90°*

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Date of reception: 06-05-2018
Date of acceptance: 09-05-2018
DOI: 10.24875/CIRU.18000437

Cir Cir. 2019;87:190-195
Contents available at PubMed
www.cirugiaycirujanos.com

y 70°. **Conclusión:** *Todos los miniimplantes presentaron un cierto grado de angulación y desplazamiento, pero los insertados en la superficie ósea a 40° tienden a presentar mejor estabilidad primaria y pueden ser inmediatamente sometidos a carga.*

PALABRAS CLAVE: *Miniimplantes. Ortodoncia. Ángulo de inserción. Método del elemento finito. Biomecánica.*

Introduction

The first attempt to use an implant for orthodontic anchorage was reported in 1945 when it was proposed that metal implants may act like anchors[1,2]. However, it was not until 1983 that mini-implants were introduced into the orthodontic clinic to provide anchorage[3-5]. The use of mini-implants for absolute anchorage eliminates secondary movement, and their use has opened a new era in the biomechanics of orthodontics because they can provide anchorage without touching the back teeth. Meanwhile, they allow movement in the anterior teeth. Once their function ends, they can be removed[6].

The successful use of mini-implants for orthodontic treatment depends on several factors such as the shape of the mini-implant, its length, and the insertion site, among others. Mini-implants are an alternative to traditional methods of anchorage in orthodontic treatment due to their versatility[7], minimal surgical invasion, and low cost[8,9].

The insertion zone of mini-implants frequently used in clinical practice is the alveolar crest; however, root injury is a risk[10-12]. To avoid root damage and ensure good stability of mini-implants, some authors have proposed insertion angles between 30 and 45°[13-16]. Other authors suggest insertion angles between 60 and 70°[17] because there is more space available near the apical region, while others favor placement at 90°[13,18] because it reduces the stress concentration and increases the probability of mini-implant stabilization.

In addition to the angle of insertion, there are still questions regarding stability and mechanical stresses around mini-implants due to the limited availability of accurate measurements that can be obtained directly from patients. Therefore, there have been many investigations in odontology using laboratory animals such as dogs, monkeys, rabbits, sheep, miniature pigs, rats, cats, goats, and mice[19]. However, the use of rabbits for research in oral implantology is a good choice due to the similarity of their bone density and diaphyseal bone composition to humans as well as economic aspects of their purchase and management due to their size and short life[20,21].

It is difficult to experimentally determine the stresses and displacements of the mini-implants at different insertion angles in an animal model through *in situ* measurement, in addition to the difficulty in controlling the parameters of the study and variations in the samples. In contrast, the finite element method is a good tool for determining the distribution of stresses and displacements in biomechanics; in our case, it can be applied to accurately determine the mechanical parameters of mini-implants. If properly used, this technique could provide reliable results to validate the results obtained by experimental studies, as there are unknown conditions imposed by the biological system that cannot be modeled[18,22].

The objective of this study is to analyze a three-dimensional (3D) finite element model (FEM) of the rabbit tibia to provide an approximate solution for estimating the response of mini-implants placed at different angles of insertion under certain given boundary conditions and to determine whether the angle is a determining factor of stability immediately after a force is applied.

Materials and Methods

FEMs were developed for the following components: (1) rabbit tibia, (2) mini-implants, and (3) springs. The model of the rabbit tibia was developed from 140 tomographic slices of the left leg of a skeletally mature male, white New Zealand rabbit, 3.5 kg in weight, employing a multislice computed tomography (CT) scanner (GE Light Speed, General Electric Company, Fairfield, CT, USA). 64 slices were made every 0.63 mm. Images were processed so that a cloud of points described the geometry of the cortical wall of the tibia and the intramedullary canal. The 3D FEM of the tibia was developed from the cloud of points. The tibia was constructed using version 11 Ansys software (Ansys Inc., Canonsburg, PA, USA) (Fig. 1). The mini-implants were modeled with SolidWorks software version 2007 (SolidWorks Corp., Concord, MA, USA) (Fig. 2) using spring contact elements.

The mini-implant was placed approximately 20 mm below the proximal epiphyses of the tibia bone.

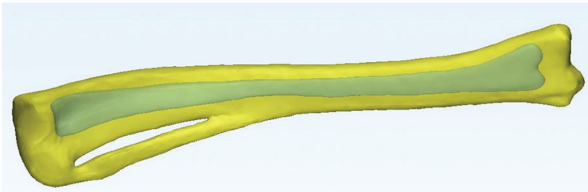

Figure 1. *Three-dimensional reconstruction of a rabbit tibia.*

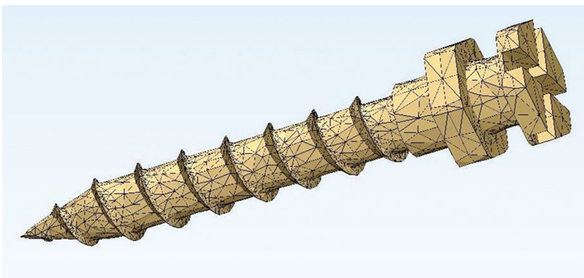

Figure 2. *Finite element model of the mini-implant.*

Placement was conducted through a single cortex (monocortical anchorage), varying the angle of insertion. A distal mini-implant was inserted 15 mm away from the first mini-implant to obtain an activation force of 2 N. This mini-implant was considered an anchor, so it was placed at 90° and inserted through both cortices of the tibia (bicortical anchoring).

All components were individually modeled and then assembled to create the finite element assembly of the tibia and mini-implant (Fig. 3). The springs were modeled with contact elements. We proposed eight case studies, in which the angle of the proximal mini-implant (6 mm long and 1.6 mm diameter) varied at 90°, 80°, 70°, 60°, 50°, 45°, 40°, and 30°, while the distal mini-implant (9 mm long and 1.6 mm diameter) was positioned at 90° in all cases. The force used in the corresponding spring was 2 N (0.76 mm wire diameter, 10 mm long, and 5 mm length of activation). The entire assembly was exported for finite element analysis to ANSYS Workbench software (version 11.0; Ansys Inc., Canonsburg, PA, USA) (Fig. 4).

We considered three different materials: Cortical bone for the rabbit tibia, Ti-6Al-4V medical grade titanium alloy for the mini-implants, and 316L stainless steel for the springs.

The mechanical properties of the bone, mini-implants, and springs were taken from literature[22-24]. All materials in the model were considered homogeneous, isotropic, and linearly elastic. For the rabbit tibia, an elasticity modulus of 13.6 GPa and Poisson's ratio of 1.3 were used. The mini-implants were modeled based on a Ti-6Al-4V titanium alloy with a modulus of the elasticity of 110 GPa and a Poisson's ratio of

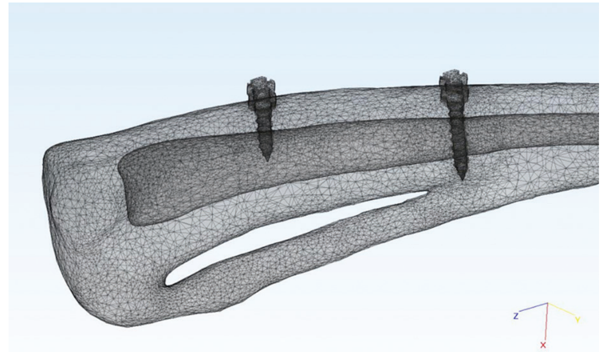

Figure 3. *Finite element model assembly of tibia and mini-implants.*

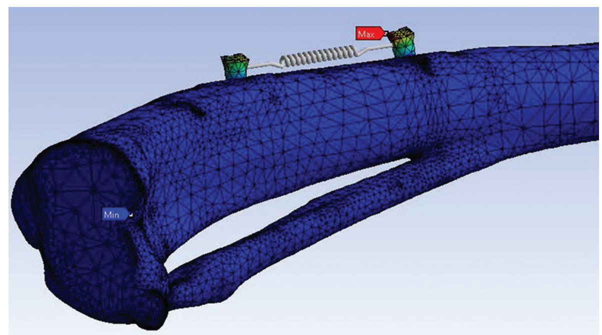

Figure 4. *Von Mises stresses for tibia, mini-implants, and spring assembly.*

0.3. The springs were modeled using 316L stainless steel with an elastic modulus of 190 GPa and a Poisson's ratio of 0.3.

The model was restricted for movement in all directions in both epiphyses, and a tensile force of 2 N was applied to the center of the mini-implants through the spring. Then, the von Mises stresses and displacement were determined within the mini-implants and the surrounding bone.

Results

The case studies showed that lower stresses occurred in both surrounding bone holes and mini-implants at angles of 40°, 90°, and 70°, indicating that the mini-implant at 40° tended to reduce stress concentrations, which provided better stability under orthodontic loads followed by 90° and 70°.

Von Mises stresses both in bone holes (area of bone drilled to insert the mini-implant) and in the different angles of mini-implants are shown in figure 5. The first values, named Bi 90, correspond to the mini-implant that was used as the anchor with bicortical insertion; the other values correspond to the mini-implants with monocortical insertion at insertion angles ranging from 90° to 30°.

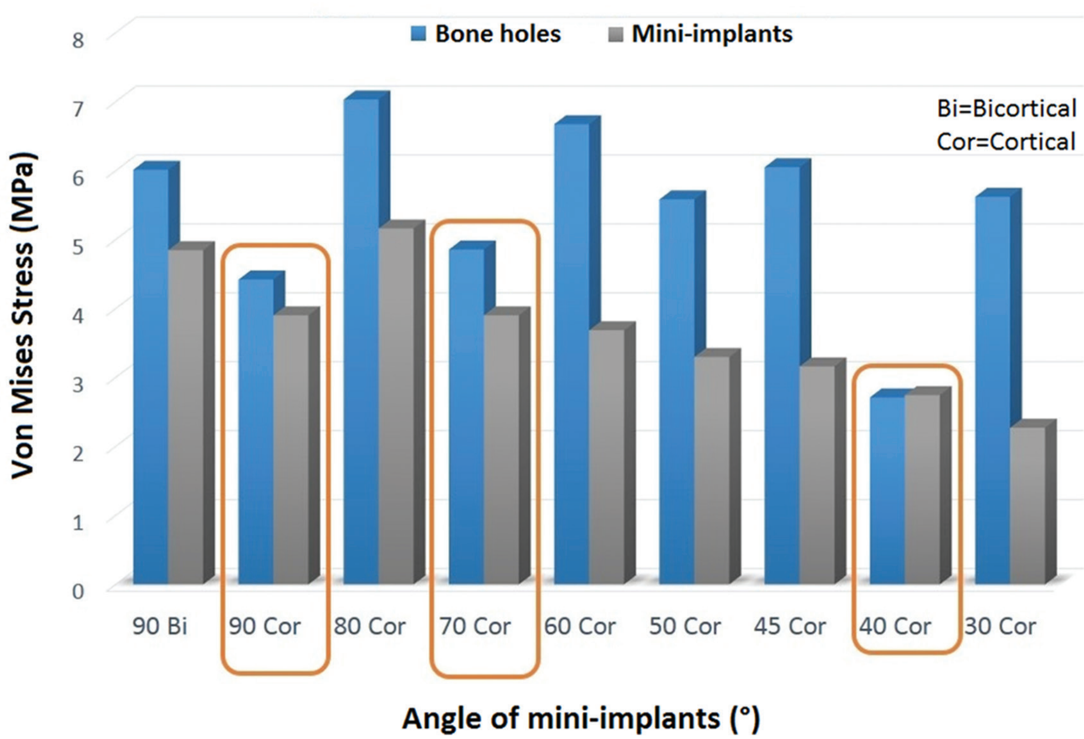

Figure 5. *Maximum von Mises stress at bone holes and mini-implants. Lower stress values are marked.*

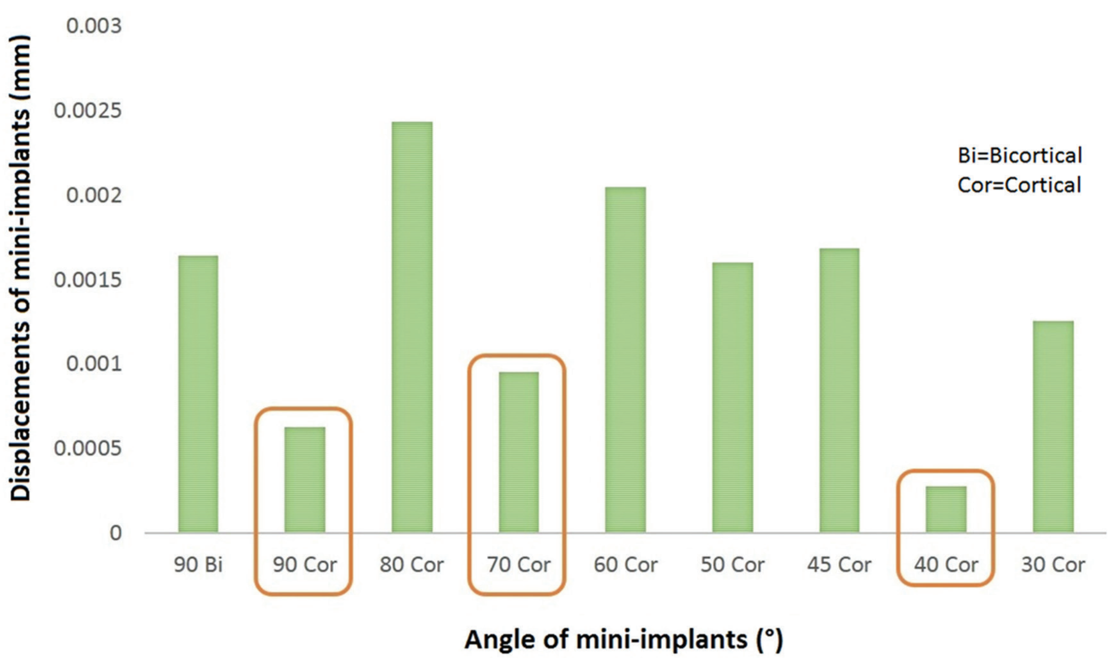

Figure 6. *Displacements of mini-implants. Minor displacements are marked.*

The movement of mini-implants with respect to the spring was less with oblique insertion at 40° than with the mini-implants inserted at 90° and 70°, indicating a slightly better stability that could be advantageous in regions with low bone quality (Fig. 6).

Discussion

The finite element method is a useful tool for the evaluation of the role of design parameters on the mechanical performance of mini-implants, as it allows us to analyze hypothetical scenarios that cannot be reproduced otherwise. In this paper, we studied the behavior of mini-implants at different insertion angles.

The results of the finite element analysis showed that all mini-implants suffered a different degree of angulation and displacement; however, mini-implants inserted at 40° with respect to the bone surface tended to reduce stress concentrations and to exhibit less displacement, which increased the probability of providing better load stability for orthodontic forces.

Of the three insertion angles with better results, the angle that showed more displacement and higher stress levels was 70° followed by 90° and 40°; however, the mini-implant at 40° showed lower levels in both variables.

There are still many questions about whether mini-implants remain stable throughout the entire orthodontic treatment[25]. A previous study showed that the mini-implants are stable during treatment[26] and that they experience some degree of displacement when they are subjected to a load. Therefore, our study focused on evaluating the stability of mini-implants implanted at the different angles considered most common in clinical practice. One study recommended that for better insertion and stability, the mini-implants must be inserted between 60° and 70°[17]. Nevertheless, our research showed that the angle of 40° was the most stable throughout the study followed by 90° and 70°.

It is clear that the oblique insertion should be at 40°, as a larger insertion angle would increase bone contact; however, it is difficult to attach springs or other traction devices. Obliquely inserting the mini-implants decreases the possibility of creating a bicortical insertion, which Brettin et al.[27] recommended for greater stability, according to their study comparing monocortical with bicortical anchorage.

The results of our study suggest that the 40° oblique insertion provided slightly higher stability than the mini-implants placed at 90°, which can be advantageous in regions with low bone quality, although the bicortical anchor greatly increases stability and the mini-implant placed at 90° ensures this stability.

Our study demonstrates the potential of the finite element method as an effective tool for the optimization of the stability of mini-implants and the minimization of risk when performing *in vivo* tests.

The validation of our results using finite element analysis by performing experimental research with an *in vivo* model (white, male New Zealand rabbits) using the mini-implants in the tibia with the best three angles of insertion found in this study (40°, 70°, and 90°) is recommended.

Acknowledgments

The authors gratefully acknowledge the work done by technician Martín Luna Méndez from CT and Ultrasound Department, at the Instituto Nacional de Rehabilitación Luis Guillermo Ibarra Ibarra.

Conflicts of interest

The authors declare no conflicts of interest related to the present manuscript.

Funding

There were no funding sources.

Ethical disclosures

Protection of human and animal subjects. The authors declare that the procedures followed were in accordance with the regulations of the relevant clinical research ethics committee and with those of the Code of Ethics of the World Medical Association (Declaration of Helsinki).

Confidentiality of data. The authors declare that no patient data appear in this article.

Right to privacy and informed consent. The authors declare that no patient data appear in this article.

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