Original Article

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Investigation of stress occurring on fixation systems and mandibular bone in fixation of mandible symphysis fractures with different plate systems

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ABSTRACT

Aims: The aim of this study is to investigate the effectiveness of carbon fiber-reinforced polyetheretherketone (CFR-PEEK) plates by comparing titanium plates with CFR-PEEK plates in the fixation of mandibular symphysis fractures.

Methods: In the study, a model that imitates the mandible was obtained with the finite element analysis method. A fracture line was created in the symphysis on the model, and a double mini-plate was applied to this line with the Champy method. Comparisons were made by assigning CFR-PEEK and titanium material properties to the plates.

Results: Von Mises stresses on screws and plates were found to be lower than those on titanium plates when CFR-PEEK plates were applied. When the stresses in the screws were examined, it was observed that the highest stresses occurred in the screws adjacent to the fracture line.

Conclusion: CFR-PEEK materials provide a more stable fixation by reducing the stresses in the fixation systems and may be a good alternative to titanium materials with their advantageous properties.

Keywords: Mandible fractures, CFR-PEEK plate, titanium plate, finite element analysis

INTRODUCTION

Mandibular fractures constitute 19-40% of fractures in the maxillofacial region.[1] The mandibular corpus, angle, and symphysis are the most frequently fractured parts of the mandible due to maxillofacial trauma, while the ramus and coronoid process are the least commonly affected regions.[2] Closed reduction and open reduction methods are employed in the treatment of mandibular fractures.[3] The use of plate and screw systems in open reduction with internal fixation has become a significant milestone in maxillofacial surgery, evolving into a routinely preferred and successful technique.[4,5] However, there is no consensus in the literature regarding the ideal treatment method for mandibular fractures. Fixation systems made from titanium alloys, due to their advantages such as high biocompatibility, ease of handling and use, and sufficient hardness and durability, are widely used in internal fixation.[6,7] But the hardness of titanium alloys is 6-7 times higher than that of the cortical bone.[8] Because it is so hard in relation to bone tissue, the titanium plates absorb all incoming stresses and prevent the formation of physiological forces in the bone, causing resorption to the bone over time.[8] In recent years, researchers have focused on investigating polymer composites with an elasticity modulus much closer to bone, aiming to overcome the disadvantages of titanium systems. For this purpose, carbon fiber-reinforced polyetheretherketone (CFR-PEEK) materials, known as "isoelastic", are becoming increasingly widely used in neurological and orthopedic surgeries, with a cortical-like elasticity module and high biocompatibility.[9] However, CFR-PEEK materials have not yet been routinely used in maxillofacial traumatology and oral surgery. Nevertheless, a review of recent literature reveals a limited number of studies evaluating the effectiveness of CFR-PEEK plates in the fixation of mandibular fractures. Therefore, the aim of this study is to investigate whether CFR-PEEK plates can serve as an alternative to titanium systems in symphysis fractures through finite element analysis.

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METHODS

Since this is a three-dimensional analysis study carried out on digital models, there is no need to obtain ethics committee permission. All procedures were carried out in accordance with the ethical rules and the principles.

In this study, the tomography of a young, healthy adult was obtained to create a geometric model of the mandible. Cone-beam computed tomography (CBCT) was utilized for scanning the jawbone. The 3M Iluma CBCT device was employed for the tomography, using a 40-second exposure mode with 120 kVp and 3.8 mA values. The captured images were transferred to the 3D-Doctor software (Able Software Corp., MA, USA). Sections obtained from the reconstruction were transferred to the 3D-Doctor software in DICOM 3.0 format, where bone tissues were separated from the sections. The segmented sections were transformed into a 3D model. The resulting 3D model underwent further processing in the 3D-Doctor software, transforming it into a smooth surface composed of elements with proportional dimensions, completing the mandibular modeling process.

For the creation of the 3D solid model and finite element stress analysis, a computer equipped with an Intel Xeon® R CPU 3.30 GHz processor, 500GB hard disk, 14GB RAM, and Windows 7 Ultimate Version Service Pack 1 operating system was used. The 3D scanning was conducted using the Activity 880 optical scanner (smart optics Sensortechnik GmbH, Sinterstrasse 8, D-44795 Bochum, Germany). Software tools such as Rhinoceros 4.0 (3670 Woodland Park Ave N, Seattle, WA 98103 USA), VRMesh Studio (VirtualGrid Inc, Bellevue City, WA, USA), and Algor Fempro (ALGOR, Inc. 150 Beta Drive Pittsburgh, PA 15238-2932 USA) were utilized for 3D modeling and analysis.

All models were considered to have linear, homogeneous, and isotropic materials. Material values defining the physical properties of structures forming models, such as cortical bone10, cancellous bone11, callus12, and titanium12 fixation systems, along with CFR-PEEK13 plates, were applied as shown in Table 1.

Table 1. Mechanical properties of simulated materials in models

Material	Young's Modulus (MPa)	Poisson's Ratio
Cortical bone	14 000	0.30
Cancellous bone	1 500	0.30
Callus	3	0.40
Titanium (plate, screw)	110 000	0.35
CFR-PEEK (plate)	15 000	0.356

The model was fixed at the anterior, posterior, superior, and lateral sides of the temporomandibular joint with zero degrees of freedom (DOF). Muscle forces were applied according to the literature.[9,11] The right side was considered as the balancing side, and the left side was considered as the working side. Von Mises stresses in plates and screws, maximum and minimum principal stresses in cortical bone, were measured in megapascals (MPa) (N/mm²), and the displacement between fracture fragments was measured in millimeters (mm) as a result of the forces applied in the study.

After creating a realistic representation of the entire anatomy of the mandible and performing 3D solid modeling, a linear fracture line with no gap between fragments in the mandibular symphysis was generated. Following the Champy method for fixation, two four-hole miniplates were placed on the superior and inferior borders of the fracture line. Two different material properties (Titanium, CFR-PEEK) were assigned to the plate material, and two different loading conditions, simulating molar and incisal loads, were applied to ensure fixation.

RESULTS

Von Mises Stresses in Plates

Under both molar and incisal loading conditions, stresses in both plate materials were concentrated at the midpoint of the plate, with stresses accumulating in the inferior plates observed to be higher than those in the superior plates (Figure 1). Von Mises stresses in the plates were found to be higher under molar loading conditions compared to stresses under incisal loading conditions. It is notable that stresses accumulated in CFR-PEEK plates under both loading conditions were significantly lower than those in titanium plates (Figure 2).

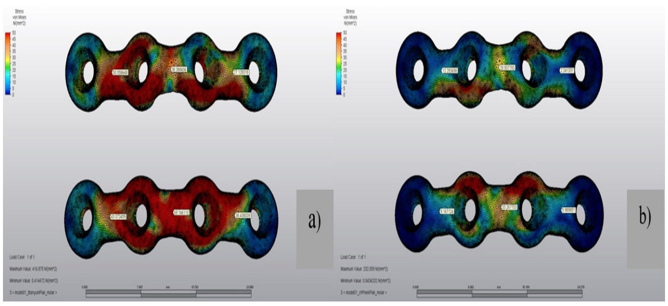

Figure 1. Von Mises stresses in plates a) Titanium b) CFR-PEEK

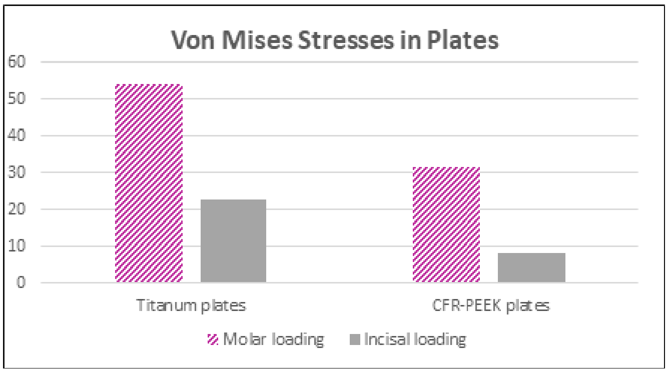

Figure 2. Von Mises stresses in plates

Von Mises Stresses in Screws

Under both loading conditions and in both plate materials, the highest screw stresses were observed in screws close to the fracture line, with the amount of stress decreasing as the screws moved away from the fracture line. When CFR-PEEK plates were applied under both loading conditions, Von Mises stresses in the screws were found to be lower (Figure 3).

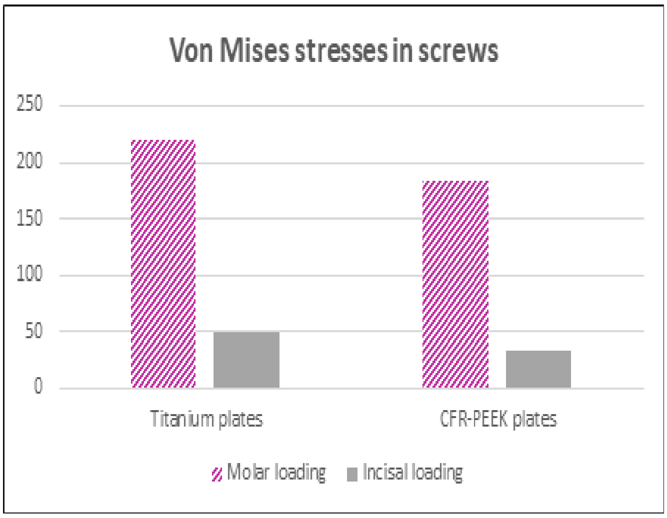

Figure 3. Von Mises stresses in screws

Maximum and Minimum Principal Stresses in Bone

The highest maximum principal stresses (Pmax, strain) in cortical bone were observed in the superior band of the titanium plate under molar loading conditions (39.095 MPa) and in the inferior band of the titanium plate under incisal loading conditions (9.855 MPa) (Figure 4). The highest minimum principal stresses (Pmin, compression) under molar loading conditions were observed in the superior band of the CFR-PEEK plate (-32.887 MPa), and under incisal loading conditions, they were observed in the inferior band of the CFR-PEEK plate (-7.039 MPa) (Figure 5). According to the study results, compressive stresses in all groups under both loading conditions were found to be below the physiological limit of 11-56 MPa.

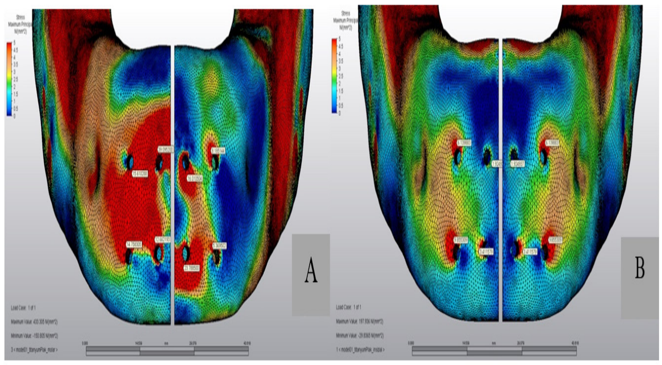

Figure 4. Highest maximum principal stresses in cortical bone
A: Titanium plate under molar loading conditions
B: Titanium plate under incisal loading conditions

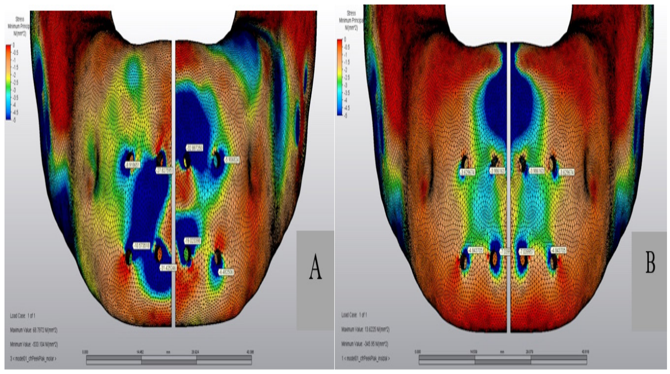

Figure 5. Highest minimum principal stresses in cortical bone
A: CFR-PEEK plate under molar loading conditions
B: Titanium plate under incisal loading conditions

Displacement Amounts Between Fractured Segments

The three-dimensional displacement amounts between the fragments were determined for the fixed ends at the inferior and superior ends of the fracture line for all three axes (Table 2). Generally, when titanium plates were applied, less intersegmental mobility was observed compared to CFR-PEEK plates. The highest displacement amounts were observed in the inferior end of the symphysis fracture with CFR-PEEK plate application under molar chewing conditions, and in the superior end with CFR-PEEK plate application under incisal biting conditions (Figure 6).

Table 2. Displacement amounts between fractured segments

			X	Y	Z	Total
Molar chewing	Titanium plate	Superior end	0.1073	0.3710	0.2399	0.4547
		Inferior end	0.4955	0.4234	0.2878	0.7125
	CFR-PEEK plate	Superior end	0.1911	0.4215	0.2645	0.5331
		Inferior end	0.5331	0.5183	0.3639	0.8279
Incisal biting	Titanium plate	Superior end	0.0293	0.4881	0.0060	0.4890
		Inferior end	0.0063	0.4407	0.0126	0.4409
	CFR-PEEK plate	Superior end	0.0384	0.4902	0.0065	0.4917
		Inferior end	0.0148	0.4505	0.0130	0.4509

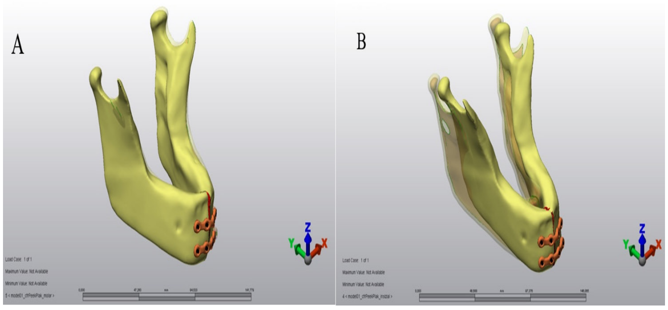

Figure 6. Displacement amounts between fractured segments with CFR-PEEK Plate application A: Molar loading B: Incisal loading

DISCUSSION

The differences in bending properties between bone and plate-screw systems cause the majority of stresses, even when excellent bone healing is achieved through internal fixation, to be borne by the plates. According to Wolff's law, the density of bone is dependent on the amount of stress accumulated on the bone, and cortical bone under very rigid plates will adapt to these conditions, leading to a more porous structure compared to healthy bone, which may result in delayed or unsuccessful bone healing.[14] Therefore, bone fragments fixed with open reduction after trauma should be exposed to physiological forces after a healthy bone healing. This is why the idea of treating fractures with isoelastic fixation systems, which have biomechanical properties close to the mechanical properties of healthy bone, has gained prominence nowadays.[9]

CFR-PEEK is an isoelastic material that is resistant to sterilization conditions, has high biocompatibility, does not create artifacts in radiographs, and most importantly, has a Young's modulus very close to cortical bone.[8] Studies have shown that CFR-PEEK is an increasingly promising fixation material, especially in orthopedic and brain surgeries, particularly in spinal cage applications.[15,16] However, there are very few studies on the use of CFR-PEEK in plate-screw systems in maxillofacial surgery.

The load-bearing properties of plates in fixation systems should be at a level that balances mechanical stability allowing bone healing with the disadvantages of excessive rigid fixation. According to our study results, the stresses accumulated in titanium plates are higher than those in CFR-PEEK plates. Similarly, under the conditions where titanium plates are applied, the average stress in screws was found to be higher than in CFR-PEEK plates. These results parallel the studies of Diker and Bayram,[9] comparing CFR-PEEK and titanium in atrophic mandible fractures, and Avcı et al.'s[17] investigation of the biomechanical stability of CFR-PEEK in angulus fractures.

One of the most important complications leading to failure in open reduction with internal fixation is screw loss. If compressive stresses in screw sockets in bone exceed physiological values, there is bone resorption and loosening of the screw. Schilemann et al.[18] reported that complications of screw loss could be reduced with the use of CFR-PEEK materials. When evaluating the possibility of bone resorption in finite element analysis, Minimum Principle stresses in cortical bone are examined. The accepted Minimum Principle threshold value for bone to survive without resorption in cortical bone is -56 MPa.[11] In our study, it was found that the highest stresses generally occurred around the screw sockets close to the fracture line, and compressive stresses in the bone in both plate materials were below the physiological threshold.

As the rigidity in fixation systems increases, the displacement amounts between fractured segments decrease.[9] In our study results, the displacement amount in CFR-PEEK plates was found to be higher than in titanium plates. However, the semi-rigid fixation feature promised by CFR-PEEK materials allows for more micro-movement between fragments, making this outcome expected.

Limitations

Finally, regarding the limitations of the current study, although we attempted to create a mandible model very close to reality with finite element analysis, to achieve more realistic results about the long-term stability and success of plate systems, we believe that this study needs to be supported by in vivo studies.

CONCLUSION

Within the limitations of the study, it has been determined that CFR-PEEK materials can provide appropriate bone healing at the fracture line and yield better results in symphysis fractures compared to titanium materials. CFR-PEEK materials are promising in the field of biomechanics and offer more advantages over traditional fixation materials due to their biomechanical properties. However, we believe that these advantageous results need further support in the field of maxillofacial surgery with more in vitro and in vivo studies.

ETHICAL DECLARATIONS

Ethics Committee Approval

The study does not require an ethics committee approval.

Informed Consent

The study does not require an informed consent.

Referee Evaluation Process

Externally peer-reviewed.

Conflict of Interest Statement

The authors have no conflicts of interest to declare.

Financial Disclosure

The authors declared that this study has received no financial support.

Author Contributions

All of the authors declare that they have all participated in the design, execution, and analysis of the paper, and that they have approved the final version.

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