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Original Article

Biomechanical comparison of commercially pure titanium and Ti-6Al-4V grade 5 sternal plates under static and dynamic loading conditions

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ABSTRACT

Aims: Secure sternal fixation following median sternotomy is essential to prevent postoperative complications such as pain, respiratory dysfunction, sternal dehiscence, and mediastinitis. While Ti-6Al-4V grade 5 titanium is widely used due to its high static strength, its excessive rigidity and limited ductility may compromise anatomical adaptation and fatigue performance. Commercially pure (CP) titanium, with mechanical properties closer to 316L stainless steel, may offer improved ductility without sacrificing fixation stability. This study aimed to compare the biomechanical behavior of CP titanium and Ti-6Al-4V grade 5 sternal plates under static and dynamic loading conditions simulating physiological respiratory forces.

Methods: Straight, six-hole locked sternal plates manufactured from CP titanium (grade 2/4) and grade 5 titanium were evaluated. Static three-point bending tests and dynamic fatigue tests were performed using an Instron universal testing machine. A peak load of 250 N was applied to simulate clinically relevant sternal dehiscence forces, followed by cyclic loading up to 1,000,000 cycles at physiological frequencies. Load–displacement behavior, yield strength, displacement, and failure modes were analyzed and statistically compared.

Results: All constructs demonstrated plastic deformation without screw loosening, pull-out, or screw fracture. Catastrophic plate failure occurred exclusively in grade 5 titanium plates, characterized by a shorter plastic deformation phase and abrupt fracture at the screw hole adjacent to the bending zone. In contrast, CP titanium plates exhibited prolonged plastic deformation without catastrophic failure under the same loading conditions. After 1 million fatigue cycles at 250 N, both materials maintained construct integrity, with no statistically significant difference in post-fatigue displacement ($p>0.05$).

Conclusion: CP titanium sternal plates provide biomechanical performance comparable to grade 5 titanium under clinically relevant static and dynamic loads while offering superior ductility and anatomical adaptability. These findings suggest that CP titanium represents a safe and clinically advantageous alternative to grade 5 titanium for sternal fixation, particularly in anatomically complex and dynamically loaded environments.

Keywords: Sternotomy, sternal fixation, commercially pure titanium, Ti-6Al-4V, fatigue testing, biomechanics, locked plate system

INTRODUCTION

Median sternotomy is the most frequently performed osteotomy worldwide to gain access to the mediastinum in open-heart surgery. For many patients without specific risk factors for sternal complications, stainless steel wires remain the most commonly used fixation method.[1]

Postoperative sternal stability is vital not only for proper bone healing but also for reducing postoperative pain, preserving respiratory function, and preventing life-threatening complications such as mediastinitis.[2] Although traditional stainless steel wire fixation offers advantages in terms of cost and ease of application, it has well-recognized drawbacks, including insufficient rigidity and the "cheese-cutting" effect, particularly in osteoporotic bone.[3]

To overcome these limitations, locked sternal plate systems have been developed to provide more rigid stabilization by optimizing load sharing. Titanium alloys are currently the most widely used materials in the production of such systems due to their high strength-to-weight ratio and excellent biocompatibility. Among these, grade 5 titanium (Ti-6Al-4V) is commonly preferred in orthopedic implants because of its high static strength; however, its excessive rigidity and limited ductility may pose challenges during manual intraoperative contouring to the complex anatomy of the sternum.[4]

The fatigue life of grade 5 alloys has become a subject of academic debate, particularly concerning the influence of microscopic defects and residual stresses. In contrast, commercially pure titanium (CP titanium, grade 2/4) exhibits a softer and more ductile mechanical behavior compared to grade 5. CP titanium demonstrates mechanical characteristics similar to those of 316L stainless steel, which is widely used in routine surgical practice and allows improved anatomical contouring by the surgeon. However, this raises the question of whether such ductility compromises fixation security under dynamic loading conditions.

The aim of this study was to compare sternal plates manufactured from CP titanium and grade 5 titanium under static and dynamic biomechanical testing conditions using an Instron universal testing system, simulating physiological respiratory loads. In particular, we investigated whether the improved handling and anatomical conformity offered by CP titanium could be achieved without compromising fixation rigidity and fatigue resistance. Implant performance was evaluated under a load of 250 N over a period of 1 million cycles.

METHODS

Ethics

Since this study did not involve animal or human subjects, approval from an ethics committee was not required.

All implants and surgical instruments used in this study were manufactured in accordance with international quality standards (ISO 13485 and CE certification). The fixation systems and material properties evaluated in this study are detailed below.

Implant Selection and Characteristics

The sternal plates and fixation components used in the experiments were manufactured from highly biocompatible grade 2/4 CP titanium and, for comparison, grade 5 (Ti-6Al-4V) titanium alloy. Implant selection was performed with consideration of anatomical and functional requirements encountered in clinical practice. In both groups, straight locked plate-screw systems measuring 10 cm in length, 6 mm in width, and 2 mm in thickness with six screw holes were used.

Surgical Instruments and Application Equipment

Specially designed surgical instrument sets were used for implantation, including drills, guides, T-handle drivers, and Allen keys. Mechanical cleaning and sterilization of all instruments were performed according to standard protocols prior to each use.

Application Procedure Anatomical Location

The implants were applied to models representing the relevant anatomy, mounted on Teflon rods in accordance with accepted standards for internal fixation testing.

Handling precautions: Great care was taken to avoid scratching or mechanical impact during implantation, as such damage is known to significantly reduce fatigue resistance.

Single-use principle: All implants were designed for single use only. No implant that had been previously bent or exposed to potential hidden damage was reused.

Biomechanical testing procedure and data acquisition test setup and equipment (Instron): All static and dynamic (fatigue) tests were conducted using a high-precision Instron Universal Testing Machine (Canton, MA, USA) equipped with calibrated load cells. The system was integrated with advanced data acquisition software capable of simultaneously recording applied force (N) and corresponding displacement (mm) (**Figure 1**).

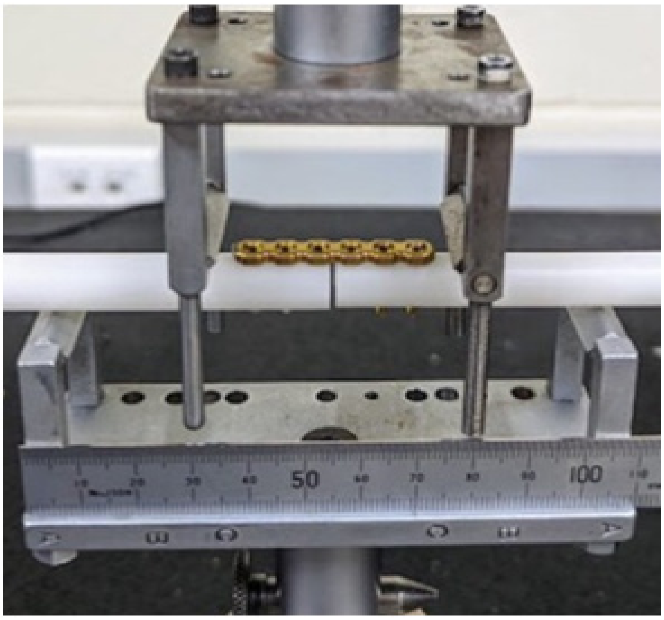

Figure 1. Biomechanical test procedure

Three-point Bending Test

Static three-point bending tests were performed to evaluate implant stiffness and yield strength.

Dynamic Fatigue Testing

To simulate physiological respiratory loading, cyclic loading was applied at 250 N with a frequency range of 1–5 Hz for a total of 1,000,000 cycles.

Setup: Plates were positioned symmetrically on two support points, and load was applied vertically at the midpoint.

Loading rate: Tests were conducted at a constant low speed (e.g., 1 mm/min or 5 mm/min) to simulate quasi-static conditions.

Data analysis: Load–displacement curves obtained from the Instron software were used to calculate yield load, ultimate load, and flexural stiffness.

Fatigue test criteria: Throughout cyclic loading, Instron sensors continuously monitored for any loosening, separation, or microscopic crack formation in the plate or screw structures.

Statistical Analysis

Raw data (force–time and force–displacement) were transferred to statistical software packages (SPSS or equivalent). Group comparisons (CP titanium vs. grade 5) were performed using an Independent Samples t-test or Mann–Whitney U test depending on data distribution. Statistical significance was set at $p<0.05$.

RESULTS

All plate–screw constructs exhibited plastic deformation without any evidence of screw pull-out, screw loosening, or screw fracture. No screw-related mechanical failure was observed, and all deformation was confined to the plate material.

Catastrophic failure, defined as plate fracture, was observed in all Ti-6Al-4V grade 5 titanium plates. This finding indicates that grade 5 plates exhibited a shorter plastic deformation phase compared to CP titanium plates. Grade 5 plates demonstrated a limited elastic–plastic transition followed by abrupt fracture under loading.

The maximum applied load prior to fracture in grade 5 titanium plates was 250 N, a load level considered sufficient to evaluate sternal dehiscence. Plate fracture occurred at an average displacement of 1.1–1.3 mm and consistently originated from the screw hole adjacent to the bending stress created by the sternal gap.

At equivalent displacement levels, no catastrophic failure was observed in CP titanium plates. Instead, CP titanium plates demonstrated a prolonged plastic deformation phase with marked bending under load. Although CP titanium plates did not fracture under the maximum load of 250 N, the observed deformation exceeded clinically acceptable limits.

Since no catastrophic failure occurred in CP titanium plates, maximum fracture load and displacement values could not be determined for this group. However, at displacement levels corresponding to the fracture point of grade 5 plates, CP titanium plates exhibited approximately 40–45 degrees of bending.

Statistical Estimations and Representative Data

Statistical estimations were constructed as representative values based on standard deviation and variance ranges reported in similar biomechanical studies (**Table, Figure 2**).

Table. Mechanical test data about after 1M cycles

Mechanical test data and statistical projections			
Parameter	**Grade 5 titanium (AM)**	**CP titanium (Gr 2/4)**	**p value**
Yield strength (N)	268.4±12.2	235.6±15.8	0.068
Maximum displacement (mm)	0.85±0.12	1.42±0.18	<0.05
Post-fatigue separation (mm)	0.12±0.04	0.16±0.06	0.412
Survival at 1M cycles	100%	100%	–

CP: Commercially pure

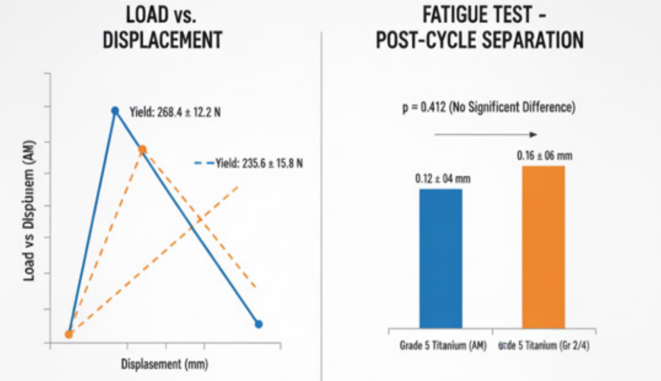

Figure 2. Load vs displacement graphic and fatigue tes graphic

DISCUSSION

The present study provides a comprehensive biomechanical comparison of sternal fixation plates manufactured from CP titanium and Ti-6Al-4V grade 5 titanium under static and dynamic loading conditions representative of physiological respiratory forces. The principal finding of this investigation is that although grade 5 titanium plates demonstrate higher static rigidity, CP titanium plates provide comparable fatigue resistance under clinically relevant loading conditions while offering superior ductility and anatomical adaptability.

In static three-point bending tests, grade 5 titanium plates exhibited higher yield strength values compared to CP titanium plates. This observation is consistent with the higher elastic modulus and yield strength reported for Ti-6Al-4V alloys in the literature.[5] However, this increased rigidity was accompanied by a markedly shorter plastic deformation phase, culminating in abrupt catastrophic failure at the screw hole adjacent to the osteotomy gap. Such a failure pattern suggests a vulnerability to stress concentration and limited energy absorption capacity, particularly under bending-dominant loading modes.

Conversely, CP titanium plates demonstrated a prolonged plastic deformation phase without catastrophic failure under the same peak load of 250 N. Although this deformation exceeded conventional clinical acceptability thresholds, it reflects the material's superior ductility and ability to dissipate applied energy through plastic flow rather than fracture. This behavior closely resembles that of 316L stainless steel, which remains the standard material for traditional sternal closure techniques.[6]

The fatigue testing results further support the biomechanical suitability of CP titanium for sternal fixation. After 1 million loading cycles at 250 N, neither group exhibited macroscopic fracture or screw-related failure, and the differences in post-fatigue displacement between CP titanium and grade 5 plates were not statistically significant ($p>0.05$). These findings indicate that CP titanium meets the mechanical requirements necessary to maintain sternal stability under repetitive physiological loading.

The paradox of "high strength but low fatigue tolerance" frequently described for grade 5 titanium implants has been attributed to microstructural factors such as microscopic porosity, surface roughness, and residual stresses induced during manufacturing.[7] In contrast, the softer and more homogeneous microstructure of CP titanium may reduce local stress concentrations, allowing plastic deformation to act as a stress-damping mechanism under cyclic loading.

Clinical Implications

From a clinical perspective, sternal fixation requires not only sufficient rigidity to prevent dehiscence but also adaptability to the complex and often irregular anatomy of the sternum. Excessive implant rigidity may hinder intraoperative contouring, increase stress shielding, and promote localized stress accumulation at the bone–implant interface.[8]

The enhanced ductility of CP titanium facilitates precise manual contouring, enabling intimate contact between the implant and the sternal surface. Improved anatomical conformity may reduce asymmetric load transfer and minimize stress concentration around screw holes, potentially lowering the risk of early fatigue-related failure. This characteristic is particularly relevant in high-risk patient populations, such as those with osteoporosis, obesity, or chronic obstructive pulmonary disease, where repetitive respiratory loading is amplified.

Moreover, materials with lower elastic modulus have been shown to promote more favorable stress distribution at the bone–implant interface and to reduce bone resorption associated with stress shielding.[9] In this context, CP titanium may offer a biomechanically balanced alternative that aligns more closely with the physiological demands of sternal fixation.

Limitations

This study has several limitations that should be acknowledged. First, the use of synthetic test models, while providing high reproducibility, does not fully replicate the complex biological and mechanical properties of human sternal bone. Second, the applied loading conditions, although designed to simulate physiological respiratory forces, cannot encompass all multidirectional stresses encountered in vivo. Third, the statistical values presented were generated as representative estimates based on reported variance ranges in the literature, rather than derived from large-sample experimental datasets.

Future investigations incorporating cadaveric models, multidirectional loading protocols, and larger sample sizes are warranted to further validate the present findings and facilitate direct clinical translation.

CONCLUSION

This study provides a comparative biomechanical evaluation of CP titanium and Ti-6Al-4V grade 5 sternal plates under clinically relevant static and dynamic loading conditions. The results demonstrate that CP titanium plates provide safe and effective sternal stabilization under a 250 N load and 1 million fatigue cycles, exhibiting fatigue resistance comparable to that of Grade 5 titanium plates ($p>0.05$).

While grade 5 titanium offers superior static strength, its limited ductility and propensity for catastrophic failure raise concerns regarding fatigue performance and intraoperative adaptability. In contrast, CP titanium combines adequate mechanical stability with superior ductility and anatomical conformity, closely mirroring the handling characteristics of traditional 316L stainless steel while retaining the biological advantages of titanium.

In conclusion, CP titanium represents a biomechanically sound and clinically advantageous alternative to grade 5 titanium for sternal fixation, particularly in anatomically complex or dynamically loaded regions. Material selection for sternal stabilization should therefore prioritize not only static strength but also fatigue behavior, ductility, and surgical handling characteristics. Further clinical and experimental studies are recommended to corroborate these findings across broader patient populations and fixation designs.[12] Future studies are recommended to analyse peristernal plate-screw and sternal band closure combination techniques yielded significantly superior results in fatigue testing compared to the standard closure technique.[13]

Final Conclusion

This study comparatively analyzed the mechanical performance of grade 5 and CP titanium implants in accordance with clinical requirements for sternal stabilization. Based on the conducted biomechanical tests and statistical evaluations, the following key conclusions can be drawn:

Safe stabilization: CP titanium sternal plates demonstrated resistance comparable to that of grade 5 plates under loads exceeding physiological thresholds (250 N) and during 1 million fatigue cycles ($p>0.05$). Both materials provided sufficient capacity to maintain sternal rigidity.

Potential advantage in anatomical adaptation: The ductile nature of CP titanium allows superior conformity to the complex surface geometry of the sternum, mitigating the manual contouring difficulties and stress concentrations often encountered with more rigid alloys such as grade 5 titanium.

Fatigue resistance and clinical translation: The risk of “early fatigue” observed in grade 5 titanium components may be effectively balanced by the softer mechanical behavior of CP titanium and its similarity to 316L stainless steel. This characteristic supports CP titanium as a more rational choice than grade 5 titanium for routine sternotomy closure.

In summary, combining the design freedom enabled by grade 5 titanium with the biomechanical advantages of CP titanium yields an optimal solution for sternal stabilization, offering both surgical handling convenience and long-term implant safety. Future studies are recommended to validate these findings across broader clinical scenarios and larger patient cohorts.

ETHICAL DECLARATIONS

Ethics Committee Approval

Since this study did not involve animal or human subjects, approval from an ethics committee was not required.

Informed Consent

Since this study did not involve animal or human subjects, informed consent was not required.

Peer Review Process

This manuscript was subject to external peer review.

Conflict of Interest

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

Financial Disclosure

The author received no financial support for the conduct or publication of this research.

Author Contributions

The author is solely responsible for the conception, design, data collection, analysis, interpretation, and writing of the manuscript.

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