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Mechanical aging and Retention Forces Assessment of Three Different Modalities of Titanium Milled bar in Implant Retained Mandibular Overdenture: An in-vitro study

Hussein Abdelhady Hussein[1], *Iman Adel El Asfahani*[1], *Shaima'a Ahmed Radwa*[1]

Aim: To evaluate the axial retention forces of three different titanium milled bar attachment systems: milled bar , milled bar with supra OT equator, milled bar with supra ball for in implant-retained mandibular overdenture.
Materials and methods: An epoxy resin model was constructed simulating completely edentulous mandible. Two implants were inserted in canine regions ,and one in the left central incisor region. Bar attachments designs were constructed by CAD/CAM technology. Experimental overdentures were to connected to either implants with milled titanium bar attachment (group I), or milled bar with supra ball attachments (group II),or milled bar with supra OT equator attachment (group III). The axial retention force was measured in Newton by universal testing machine for each attachment system at base line (T0) to (T11) which simulating five years of the overdenture function (T11 after 5400 cycles of insertion and removal).
To compare the three groups to each other; one way-ANOVA followed by Tukey post hoc test, were used to compare between more than two groups in non-related samples.
Results: The milled bar with supra ball attachments had a significantly highest retention forces (142 Newton) followed by milled bar with equator attachments (118.65 Newton), while the lowest one was milled bar (111.40 Newton) at base line. The loss of retention force continued throughout the study to reach (22.96 Newton) for milled bar with ball, (20.6 Newton) for milled bar with equator, and for milled bar (18.74 Newton) at the end of the study.
conclusion: The retention forces for the milled bar with ball attachment systems demonstrated significantly higher retention forces than those for the milled bar with OT equator, milled bar after cyclic insertion and removal.

Keywords: Strain gauge, Ti Si snap, Locator attachment, overdenture

1. Prosthodontics Department, Faculty of Dentistry, Minia University., Egypt.
Corresponding author: Shaima'a Ahmed Radwa, email: shaimaa.radwan@mu.edu.eg

Introduction

Mandibular implant-retained or supported overdentures have greatly enhance patients' quality of life compared to tissue-supported conventional complete dentures.[1,2,3]

Implant overdenture attachments have been shown to significantly enhance mastication, speech, denture stability, and retention.[4] Mandibular overdentures supported by more than two implants, typically splinted using a bar attachment, are commonly recommended to provide greater support from the implants compared to the alveolar ridge mucosa. This approach effectively compensates for atrophied posterior segments or areas with high muscular attachments, thereby reducing the need for denture base extension. [5]

Bar and ball attachments are widely recognized for achieving high patient satisfaction in retaining overdentures. When sufficient primary stability of the implants is ensured, a bar can be utilized to support an immediate restoration following implant placement. One notable advantage of the bar system is its ability to provide enhanced denture stability. Combining bar and clip attachments further optimizes the system by reducing loading forces on the implants and compensating for implant misalignment. The bar serves to splint the implants, while the clip ensures proper positioning of the prosthesis' undersurface, resulting in excellent retentive capacity.[6,7,8,9,10]

Recent advancements have introduced metallic milled bars designed to splint implants and achieve full stabilization of overdentures in both the mandible and maxilla. These bars, fabricated using CAD/CAM (computer-aided design and computer-aided manufacturing) technology, have demonstrated high oral health-related quality of life outcomes and a low incidence of complications.[11]

The evaluation of retention can be conducted through both in vitro and in vivo studies. In vitro studies offer greater control over variables, as they can be repeated under standardized conditions. These studies simulate teeth, periodontal ligaments, and supporting tissues, which inherently differ among individuals, thereby allowing for precise measurement of specific parameter changes. Dislodging forces could be measured using a universal testing machine, with maximum dislodging forces defined as the highest forces recorded before the complete separation of attachment components from the abutments. Studies have demonstrated that the maximum force required to dislodge an implant overdenture from its abutment varies with the number of insertion-removal cycles.[12,13]

This raises an important question in prosthodontics: does the design of attachment systems influence the retention force of mandibular implant-retained overdentures? The null hypothesis of this study posits that the design of the attachment system has no significant effect on the retention force of mandibular implant-retained overdentures.

Materials and Methods

Model Preparation

A commercially available rubber mold of a completely edentulous mandible (Tri-mold, Tokyo, Japan) was used to create two identical models. The first model was poured using epoxy resin (Kemapoxy 150, CMB International, Giza, Egypt), and the second with dental stone. Both models were fabricated according to the manufacturer's instructions to ensure consistent size and dimensions. An acrylic denture with artificial teeth was constructed on the stone model to serve as a template during implant placement.

Implant Placement

For standardization, all procedures were performed on the same epoxy resin mandibular model. Three identical implants (Flotecno SRL, Turati 38, Milano, Italy) with dimensions of 3.7 mm in diameter and 11.5 mm in length were inserted at predetermined locations[14]:

bilaterally in the canine regions and at the left central incisor region. Implant placement parallism was standardized by using a milling machine to ensure parallel alignment. Small amounts of mixed epoxy resin were poured into the prepared osteotomy sites before inserting the implants, ensuring proper stabilization. Figure (1)

Figure 1: Implant placement parallelism was standardized by using a milling machine to ensure parallel alignment

Prosthetic Phase and Attachment System Grouping

Three groups of attachment systems were designed for this study:

- **Group I**: Milled titanium bar.
- **Group II**: Milled titanium bar with supra ball attachments.
- **Group III**: Milled titanium bar with supra OT equator attachments.

Bar Design and Manufacturing

Scan bodies (Scan Abutment; Rhein 83 SRL, Bologna, Italy) were attached to the implants, and the model with implants was scanned to produce a digital STL file. The design of the bar was created using specialized software (Exocad Dental GmbH, Rosa-Parks-Str. 2, 64295 Darmstadt, Germany).

For **Group I**, the titanium bar was designed with axial walls inclined at 4–6 degrees to ensure a common insertion path and to provide a secure frictional fit during function.

For **Groups II and III**, the milled bar was constructed with the same specifications as Group I, with the addition of two preformed rounded recesses on the superior surface.[14] These recesses were located between the three implants in the lateral incisor regions to accommodate the supra-structure attachments. Figure (2)

- **Group II**: Two supra ball attachments (2.5 mm diameter, single-threaded spheres; Rhein 83 SRL, Bologna, Italy) were carefully placed and screwed into the recesses on the superior surface of the bar to ensure a stable fit.
- **Group III**: Two supra OT equator attachments (single-threaded spheres, normal size; Rhein 83 SRL, Bologna, Italy) were similarly positioned and secured in the same recesses.

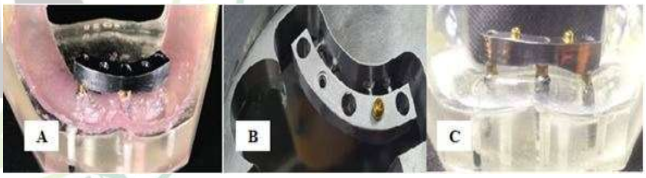

Figure 2: Bar attachment A. Milled bar B. bar Recesses were located between the three implants in the lateral incisor regions to accommodate the ball supra-structure attachments .c. Milled bar with OT equator

Bar Fabrication

The virtual bar designs for all groups were milled from a homogenous solid titanium disc (Ti5 Disc; Scheftner GmbH, Germany) using a milling machine (Emar ED5X; 10th of Ramadan City, Sharqia Governorate, C2 Industrial Zone, Egypt). The resulting titanium bars were checked for fit on the epoxy resin cast and attached to the equator attachments using elastic Seeger rings (OT Equator Passive Bar Seeger System, Rhein 83 SRL, Bologna, Italy). The Seeger rings allowed passive seating of the titanium bar and ensured proper fit and stability. A representative bar with its attachment system is shown in Figure (2)

Construction of Skeleton Metallic Frameworks

One distinct skeleton metallic frameworks was designed and fabricated for this study. The framework was constructed to accommodate Group I (milled titanium bar attachment), Group II (milled titanium bar with supra ball attachments) and Group III (milled titanium bar with supra OT equator attachments). The framework included two openings corresponding to the preformed recesses on the bar to house the metal housings of the ball and OT equator attachments.

The metallic framework was designed using CAD software and fabricated through a 3D laser metal printing process (Vm120, Vulcantech GmbH, Neue Speicherstraße 9, 30453 Hanover, Germany). The framework was printed using a cobalt-chromium alloy (EOS Cobalt Chrome SP2; EOS GmbH, Robert Stirling Ring 1, D-82152 Krailling, Munich, Germany) via a selective laser melting (SLM) technique. After printing, the frameworks were polished and finished to ensure proper fit and functionality.

The framework was designed to include three metallic rods emerging from the bilateral first molar regions and the midline lingually. These rods were unified at the geometric center of the mandible by a rounded metallic plate. Additionally, two triangular hooks were incorporated into the plate design to facilitate engagement with the universal testing machine. Figure (3)

Figure 3: Construction of overdenture metallic framework; (A) 3D laser metal printing of Co-Cr framework. (B) Fitting surface of metallic framework. (C) The over denture after finishing and polishing.

Construction of Overdentures

One mandibular overdentures was fabricated around the two metallic frameworks. This was constructed using stone casts duplicated from the epoxy resin cast, which included the bar or the bar with supra attachments. Duplication was carried out using a modified agar-agar impression material (Superb Jelly, Mestra, Talleres Mestraitua SL, Txorierri Etorbidea 60, 48510 Vizcaya, Spain).

Fully contoured waxed-up dentures were created, flasked, and processed using conventional heat-activated acrylic resin. After curing, the dentures were polished and prepared for the pick-up procedure. Figure (3)

Simulation of Mucosa Covering the Residual Ridge

To simulate the soft tissue of the edentulous ridge, a 2 mm space was created in the residual ridge area of the epoxy resin model. Multiple 2 mm deep holes were drilled into the ridge using a #5 round bur (Dental Bur - Round 5 RA 22 mm; Unit 29, Duleek Business Park, Duleek, Co Meath, A92 N72W, Ireland). The remaining epoxy resin between the holes was then removed using a cylindrical carbide cutter bur (Large Tubular HP Carbide Bur; Unit 29, Duleek Business Park, Duleek, Co Meath, A92 N72W, Ireland).

A self-cured silicone soft liner (Mollosil, Detax GmbH & Co. KG, Carl-Zeiss Str. 4, 76275 Ettlingen, Germany) was packed into the 2 mm space to create a uniform resilient layer, simulating the mucosa of the edentulous ridge. This provided a consistent and realistic soft tissue simulation across all test groups.

Pick-Up Procedure

To ensure proper seating of the overdenture and sufficient clearance between the fitting surface and the metal housing of the attachments, the fitting surface of the overdenture was reduced. A pick-up procedure was performed using chemically activated acrylic resin at the dough stage. During the curing process, the overdenture was seated, and finger pressure was applied until the resin set completely.

The same steps were repeated after measuring the retention force of Group I to allow proper pick-up and attachment of the supra ball attachments in Group II and OT equator attachment in Group III.

Retention Evaluation

Retention forces were measured using a universal testing machine (LLOYD LRX, LLOYD Instruments Ltd., Fareham, Hampshire, UK). A vertical arm with a hook extension was secured to the machine's clamps. The epoxy resin model with the overdenture assembly was positioned such that the hook engaged passively with the triangular hangers on the metallic plate of the framework. Proper care was taken to ensure that the hook fit securely into the triangular extensions and that the prosthesis was firmly gripped in the machine's lower compartment.

Gradual tensile load was applied until the maximum retentive force was recorded. The retentive forces were measured under simulated conditions designed to replicate real-world use.

Simulation of Long-Term Use and mechanical aging

To simulate the daily use of the overdenture, it was assumed that the prosthesis would be removed and reinserted three times per day. Repeated cycles of removal and insertion were performed to replicate prolonged intraoral function.

Retention forces were evaluated at specific time intervals, including baseline (T0), after 30 cycles (T1, representing 10 days of use), 90 cycles (T2, representing 1 month), 270 cycles (T3, representing 3 months), 540 cycles (T4, representing 6 months), 810 cycles (T5, representing 9 months), and 1080 cycles (T6, representing 1 year). Further evaluations were conducted at 1620 cycles (T7, representing 1.5 years), 2160 cycles (T8, representing 2 years), 3240 cycles (T9, representing 3 years), 4320 cycles (T10, representing 4 years), and 5400 cycles (T11, representing 5 years of intraoral functioning). Figure (4)

Figure 4: showing the application of retention test using universal testing machine

Results

Mechanical Aging and Retention Force over 5-Year Follow-Up

Descriptive statistical data in Newton were collected and presented in the form of mean, standard deviations Table (1), and statistical testing was performed using /assistat software version 7.7. This study assessed the mechanical aging and retention force of three attachment systems – milled titanium bar, milled bar with supra ball attachment, and milled bar with supra equator attachment – over a 5-year period (5400 cycles). The retention force measurements at various time points (T0–T11) revealed significant retention force degradation across all systems, with statistically significant differences observed between the groups at all time points ($p < 0.001$). The data were explored for normality using Kolmogorov-Smirnov and Shapiro-Wilk tests, data showed parametric (normal) distribution. To compare the three groups to each other; one way-ANOVA followed by Tukey post hoc test, were used to compare between more than two groups in non-related samples.

Table 1: The mean, standard deviation (SD) values of mechanical aging (retention) of different groups.

	Attachment types									
Interval symbol period of used cycles	Milled titanium bar			Milled bar with supra ball attachment			Bar with supra equator attachment			p-value
	Mean± SD		Percentage of retention loss relative to baseline	Mean± SD		Percentage of retention loss relative to baseline	Mean± SD		Percentage of retention loss relative to baseline	
T0 (Baseline)Zero level	111.40 cA	3.76	--------------	142.52 aA	2.70	------	118.65bA	0.85	--------	<0.01**
T1 (10 days) 30 cycles	96.24 bB	2.16	13.6060	127.2 5aB	3.16	10.7140	99.49bB	4.2	16.14834	<0.01* *
T2 (After 1month) 90 cycles	80.12cC	1.76	28.0745	99.58aC	2.12	30.1266	86.82bC	1.71	26.8268	<0.01**
T3 (After 3month) 270 cycles	63.68cD	1.69	42.8354	76.92aD	2.37	46.0320	72.32bD	1.85	39.04762	<0.01**
T4 (After 6month) 540 cycles	61.77 bD	0.90	44.5512	70.38aE	1.26	50.6162	67.42aE	1.02	43.17741	<0.01**
T5 (After 9month) 810 cycles	54.58 cE	1.62	51.0033	65.93aE	0.90	53.7459	62.48bF	2.04	47.34092	<0.01**
T6 (After 1year) 1080 cycles	50.65bE	0.56	54.5271	59.43aF	1.08	58.3046	56.41aG	1.36	52.45681	<0.01**
T7 (After 1.5years) 1620 cycles	43.54cF	1.48	60.9167	53.40 aG	1.36	62.5390	47.56bH	1.12	59.91572	<0.01* *
T8 (After 2years) 2160 cycles	42.75 bF	1.58	61.6218	47.39 aH	1.84	66.7547	45.4 abH	0.94	61.7362	<0.01**
T9 (After 3years) 3240 cycles	32.75 bG	0.74	70.6018	38.18 aI	1.45	73.2119	38.57 aI	1.06	67.49263	<0. 01**
T10 (After 4years) 4320 Cycles	30.36 bG	1.05	72.7473	35.88 aI	0.97	74.8264	35.09 aI	0.43	70.42562	<0.01* *
T11 (After 5years) 5400 cycle	18.74 bH	0.82	83.1824	22.96aJ	0.98	83.8909	20.6abJ	0.86	82.63801	<0. 01**
p-value	<0.01**			<0.01**			<0.01**			

** significant at level of 1% of probability (p<0.01) ns; non-significant (p>0.01),Significant minimum difference (SMF)for columns lower case letters, while for rows upper case letters

Key observations are summarized below:

1.Baseline Retention Forces (T0)

At baseline (T0), the highest retention force was recorded in the milled bar with supra ball attachment (142.52 ± 2.70 N), followed by the bar with supra equator attachment (118.65 ± 0.85 N) and the milled titanium bar (111.40 ± 3.76 N). This initial difference was statistically significant ($p < 0.001$).

2.Short-Term Changes (T1–T3, 10 days to 3 months)

By T1 (30 cycles, 10 days), all groups experienced a significant reduction in retention force. The milled titanium bar showed a retention loss of 13.61% (96.24 ± 2.16 N), while the supra ball and supra equator attachments had losses of 10.71% (127.25 ± 3.16 N) and 16.15% (99.49 ± 4.20 N), respectively .

After 3 months (T3, 270 cycles), the retention forces further declined, with the milled titanium bar showing a 42.84% reduction (63.68 ± 1.69 N), the supra ball attachment a 46.03% reduction (76.92 ± 2.37 N), and the supra equator attachment a 39.05% reduction (72.32 ± 1.85 N). All differences between groups remained statistically significant ($p < 0.001$)

3.Mid-Term Changes (T4–T7, 6 months to 1.5 years

At T4 (540 cycles, 6 months), retention forces continued to decrease across all groups. The milled titanium bar showed a 44.55% retention loss (61.77 ± 0.90 N), while the supra ball attachment exhibited a greater loss of 50.62% (70.38 ± 1.26 N). The supra equator attachment group experienced a similar loss of 43.18% (67.42 ± 1.02 N).

By T7 (1620 cycles, 1.5 years), retention forces in the milled titanium bar group dropped to 43.54 ± 1.48 N (60.92% loss). The supra ball and supra equator attachment groups retained 53.40 ± 1.36 N (62.54% loss) and 47.56 ± 1.12 N (59.92% loss), respectively. Differences remained significant between the groups ($p < 0.001$)

4.Long-Term Changes (T8–T11, 2 to 5 years)

Over the long-term follow-up, all groups exhibited substantial retention force degradation. At T8 (2160 cycles, 2 years), retention forces were 42.75 ± 1.58 N for the milled titanium bar (61.62% loss), 47.39 ± 1.84 N for the supra ball attachment (66.75% loss), and 45.40 ± 0.94 N for the supra equator attachment (61.74% loss)

By T11 (5400 cycles, 5 years), retention forces reached their lowest levels: 18.74 ± 0.82 N (83.18% loss) for the milled titanium bar, 22.96 ± 0.98 N (83.89% loss) for the supra ball attachment, and 20.60 ± 0.86 N (82.64% loss) for the supra equator attachment. Despite the retention losses, the supra ball attachment consistently retained higher forces compared to the other groups, with significant differences observed at all time points ($p < 0.001$). This pattern of retention loss continued for the three groups Figure (5).

The interaction between attachment type and time was significant ($p < 0.001$), indicating distinct retention force degradation patterns for each group. The supra ball attachment system demonstrated superior retention throughout the study, while the milled titanium bar exhibited the most pronounced early degradation. Figure(5)

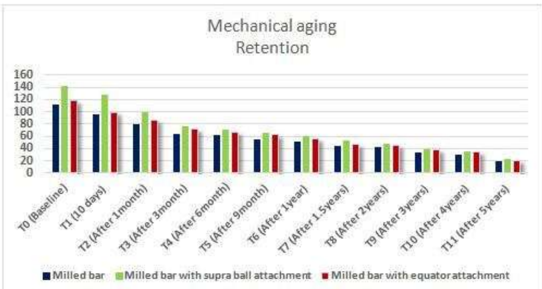

Figure 5: The changes of retention forces among three groups after removal and insertion cycles.

Discussion

The present study evaluated the retention force changes in three bar attachment designs – milled titanium bar, milled bar with supra ball attachment, and milled bar with supra OT equator attachment – constructed using advanced CAD/CAM and additive manufacturing (AM) technologies. [10] These technologies provide precise, custom-fitted frameworks with minimal porosity and misfit, overcoming limitations associated with conventional fabrication methods. The CoCr frameworks fabricated via selective laser melting (SLM) enhance mechanical properties, including tensile strength and corrosion resistance, contributing to the durability of the tested attachments. [15,16,17,18,19,20] The attachments were subjected to 5400 insertion-removal cycles, simulating approximately 5 years of clinical use, assuming three removals daily for oral hygiene maintenance .[21,22,23,24]

The results showed a significant reduction in retention force over time for all attachment systems. Retention loss from baseline (T0) to the 5-year mark (T11) was 83.18% for the milled titanium bar, 83.89% for the supra ball attachment, and 82.64% for the supra OT equator attachment. Despite the notable degradation, the supra ball attachment maintained the highest retention forces at all intervals, likely due to its increased surface contact area, precision of fit, and frictional retention. This finding is consistent with Eldidi and Abdelhakim (2021), who reported that designs enhancing surface interaction exhibit superior retention. However, the supra ball attachment also demonstrated greater wear, attributable to material loss in the nylon caps, which impacted its retention characteristics over time. In contrast, the milled bar attachment, prone only to metal wear, exhibited the fastest early retention degradation due to its simpler design and reduced frictional engagement. [25]

The observed retention losses in all systems can be linked to mechanical aging, friction reduction, and wear between the titanium milled bar and the CoCr frameworks. These findings align with Moharrami et al. (2013), who noted that oxidized titanium alloys exhibit higher hardness than CoCr alloys, accelerating the wear of the latter. Nonetheless, the tripod implant configuration used in this study likely minimized excessive retention loss by distributing forces more evenly compared to a linear arrangement. Retention forces of 18.74 N (milled bar), 22.96 N (supra ball), and 20.60 N (supra OT equator) after 5 years remain clinically acceptable, as forces within 5–20 N are adequate for overdenture stabilization during function .[26]

Attachment retention forces ranging from 5 to 20 N were considered to be sufficient to stabilize over denture during function. Based on this information, the retention forces of attachment systems tested in the present study would be acceptable after 5 years (mean of 18.74N for milled bar attachments, and 22.96 N for milled bar with supra ball attachments,and 20.6 N for milled bar with supra OTequator attachment after 5,000 insertion-separation cycles). This also may be attributed to using 3 implants in tripod design which creates an angular relationship between the implants instead of a straight-line relationship. [27,28,29,30]

Conclusion

Within the limitations of this in vitro study, it is concluded that the design of attachment systems significantly impacts the long-term retention of implant-retained mandibular overdentures. The supra ball attachment consistently outperformed other designs, providing higher retention forces over the 5-year testing period. When the retention of milled bar attachments diminishes, it may be restored by incorporating additional supra-attachments. However, the study's-controlled conditions, absence of dynamic occlusal loads, and lack of oral environment simulation (e.g., saliva) limit its direct clinical applicability. Future studies should focus on in vivo performance to better evaluate the longevity and mechanical properties of attachment systems under real-world conditions.

Clinical Implications

This study underscores the progressive retention loss associated with mechanical aging in attachment systems. While all systems experienced significant reductions over 5 years, the supra ball attachment maintained the highest retention forces, making it a preferable choice for long-term prosthetic applications.

When the milled bar loses its frictional retention by time, it can be restored by adding supra ball or OT equator attachments to its design. The retention forces of attachment systems tested in the present study may be acceptable after 5 years of denture usage following the same conditions.

Clinicians should consider these findings in their attachment system selection and maintenance strategies. Further research is warranted to explore materials and designs that could mitigate retention loss over time.

Ethics approval

The present study was conducted in faculty of dentistry, Minia university after the approval of Minia dentistry ethical committee No:109,Decision no:955,Date30/7/2024.

Competing interest

The author declare that :they have no competing interest.

Data availability

The datasets used and analyzed during the current study are available from the corresponding author upon reasonable request.

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