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The Effect Of Use And Sterilization On Orthodontic Arch Wire On Load Deflection Characteristics

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Abstract

Objective: This study evaluated the influence of clinical use and subsequent steam sterilization on the load-deflection characteristics of superelastic Nickel-Titanium (NiTi) orthodontic archwires.
Materials and Methods: Forty-five 0.016-inch NiTi archwires were divided into three groups: Group 1 (As-received/Control), Group 2 (Retrieved after 4 weeks of clinical use), and Group 3 (Retrieved and sterilized at 134°C). Mechanical properties were assessed via a three-point bending test in a 37°C water bath. Loading and unloading forces were recorded at deflection intervals up to 3.0 mm. Data were analyzed using one-way ANOVA and Tukey's post-hoc tests ($p<0.05$).
Results: Clinical use and sterilization significantly increased loading forces compared to the control ($p<0.05$). Conversely, the unloading plateau forces decreased by 12% in the retrieved group and 17% in the sterilized group. A higher incidence of permanent deformation was observed in the recycled groups.
Conclusion: Both clinical exposure and steam sterilization degrade the superelastic performance of NiTi archwires, leading to less predictable force delivery. Clinicians should be aware that reprocessing these wires may compromise treatment efficiency.

Introduction
Orthodontic treatment relies heavily on the predictable mechanical behavior of archwires to facilitate controlled and efficient tooth movement [1]. The archwire serves as the primary actuator in fixed orthodontic appliances, transmitting forces from the bracket system to the dentition to achieve desired tooth positions. The success of orthodontic mechanotherapy depends on the ability of archwires to deliver forces within a therapeutic range that promotes tooth movement while minimizing undesirable tissue responses, including root resorption, hyalinization, and patient discomfort. Among the materials utilized in contemporary orthodontic practice, Nickel-Titanium alloys have become the gold standard for the initial leveling and aligning phases of treatment due to their unique properties of superelasticity and shape memory [2]. Superelasticity, also referred to as pseudoelasticity, describes the ability of the alloy to undergo large reversible deformations without permanent plastic strain, while shape memory refers to the capacity to recover a predetermined shape upon heating through a phase transformation. These unique mechanical characteristics arise from a reversible martensitic phase transformation that occurs in the alloy at temperatures relevant to the oral environment. The clinical significance of these properties lies in the ability of Nickel-Titanium archwires to deliver relatively constant, light forces over a wide range of activations, which is essential for minimizing tissue trauma, preserving pulpal vitality, and reducing patient discomfort during the critical early stages of treatment when initial leveling and alignment are being established [3].
In clinical practice, the economic feasibility and environmental sustainability of orthodontic care have prompted consideration of recycling and re-sterilizing archwires [4]. The rationale for reprocessing archwires includes cost reduction for patients and orthodontic practices, as well as decreased material waste associated with single-use components. However, the safety and mechanical reliability of reprocessed archwires remain subjects of ongoing investigation, as the cumulative effects of intraoral exposure and sterilization protocols may alter the critical mechanical properties upon which predictable force delivery depends.
During their tenure in the oral cavity, archwires are subjected to a complex environment characterized by fluctuating temperatures ranging from approximately 5°C during ingestion of cold substances to 55°C or higher during consumption of hot beverages; varied pH levels from dietary intake, plaque accumulation, and microbial metabolic activity; and constant mechanical loading resulting from mastication, occlusion, and orthodontic activations [5]. These factors are known to induce surface corrosion, pitting, and the absorption of hydrogen, all of which may potentially alter the internal crystalline structure and the transition temperatures of the alloy [6]. Surface degradation can create stress concentration sites that may serve as initiation points for fracture, while hydrogen absorption can embrittle the material and alter its superelastic behavior.

Furthermore, the sterilization process itself, most commonly conducted via steam autoclaving, exposes the wires to high temperatures, typically ranging from 121°C to 134°C, and elevated pressures. Preliminary research has suggested that repeated thermal cycling during sterilization may induce phase transformations or aging effects in Nickel-Titanium alloys, which could significantly modify their load-deflection characteristics [7, 8]. The thermal exposure associated with autoclaving may shift the austenite finish temperature of the alloy, potentially altering the temperature range over which superelastic behavior is clinically expressed. Additionally, repeated cycles of heating and cooling may induce precipitation of secondary phases or alter the distribution of dislocations within the crystalline lattice, both of which can affect the mechanical response of the material.
While several studies have examined the effects of sterilization or clinical use in isolation, there remains a notable lack of comprehensive data regarding the cumulative impact of both factors on the force delivery profiles of modern superelastic archwires [9]. Most existing research has evaluated either the effects of intraoral aging or the effects of sterilization separately, without considering the combined effects that would occur in the context of archwire recycling. Understanding the interaction between these variables is essential for determining whether reprocessed archwires can deliver forces that remain within the therapeutic window required for efficient and safe tooth movement.
The purpose of this study is to evaluate and compare the load-deflection characteristics of as-received, clinically used, and post-clinical sterilized orthodontic archwires. By quantifying changes in the loading and unloading plateau forces, which represent the forces delivered during activation and deactivation of the archwire, this research aims to determine the clinical viability and mechanical reliability of reprocessed archwires in a simulated clinical environment. The findings will contribute to evidence-based decision-making regarding the practice of archwire recycling, balancing considerations of cost-effectiveness and sustainability against the requirement for predictable mechanical performance essential to successful orthodontic outcomes.

Materials and Methods

Sample Selection and Grouping

A total of 45 pre-formed 0.016-inch superelastic Nickel-Titanium archwires were utilized in this study. All wires originated from the same manufacturing lot to ensure consistency in initial alloy composition, mechanical properties, and thermomechanical processing history, thereby minimizing variability that could arise from inter-lot differences. The selection of the 0.016-inch dimension is clinically relevant, as this wire size is commonly employed during the initial leveling and aligning phases of orthodontic treatment, where superelastic properties are most critical.
The samples were randomly assigned to three experimental groups, with 15 specimens allocated to each group to provide adequate statistical power for detecting differences in load-deflection characteristics.
Group 1 served as the control group, consisting of as-received wires tested directly from the manufacturer's packaging. This group established the baseline mechanical performance of the archwires prior to any intraoral exposure or sterilization.
Group 2 comprised retrieved wires obtained from orthodontic patients after a 4-week clinical leveling and aligning phase. The 4-week duration was selected to represent a typical interval between orthodontic adjustment appointments, during which archwires are subjected to intraoral environmental conditions and continuous mechanical loading. Inclusion criteria for patients contributing to this group included a non-extraction treatment plan, as extraction cases may involve different force requirements and wire engagement patterns, and the absence of heavy smoking or systemic conditions affecting oral pH, as these factors could introduce uncontrolled variability in the intraoral environment.
Group 3 consisted of wires retrieved after a 4-week clinical phase identical to Group 2, which were subsequently subjected to a standardized steam sterilization cycle. This group was designed to evaluate the cumulative effect of both intraoral exposure and the sterilization process on the mechanical properties of the archwires.

Clinical and Sterilization Protocols

Retrieved wires from Groups 2 and 3 were carefully removed from the orthodontic brackets using distal end cutters, taking care to avoid unnecessary mechanical deformation that could alter the load-deflection characteristics beyond the intended experimental variables. Any residual composite material, adhesive, or debris adhering to the wire surfaces was gently cleaned using a soft-bristle brush and distilled water to remove contaminants that might interfere with subsequent mechanical testing or sterilization. The cleaning process was performed with minimal handling to avoid introducing additional surface damage or work hardening.
Samples assigned to Group 3 were packaged individually in standard sterilization pouches to maintain sterility and to simulate clinical sterilization protocols. The pouches were processed in a benchtop steam autoclave, a device commonly used in orthodontic practices for instrument sterilization. The sterilization cycle was conducted at 134°C at a pressure of 2.1 bar for a holding time of 5 minutes, followed by a 20-minute drying phase. These parameters represent a standard vacuum-assisted steam sterilization cycle commonly employed for heat-tolerant orthodontic instruments and materials. The drying phase ensures complete removal of residual moisture that could otherwise contribute to surface corrosion or interfere with mechanical testing.

Mechanical Testing Procedure

The load-deflection characteristics of the archwires were evaluated using a three-point bending test conducted on a Universal Testing Machine equipped with a 10 Newton load cell. This testing configuration was selected because three-point bending closely simulates the clinical loading conditions experienced by orthodontic archwires during engagement in brackets, providing clinically relevant measurements of force delivery.

To simulate the oral environment, the testing apparatus was submerged in a temperature-controlled water bath maintained at 37°C ± 0.5°C throughout the testing procedure. This temperature was selected to approximate the average intraoral temperature and to ensure that the superelastic behavior of the Nickel-Titanium alloy was assessed under conditions relevant to clinical use. The water bath also served to maintain consistent testing conditions across all specimens, eliminating temperature-related variability in the mechanical response.

Each archwire specimen was placed on two cylindrical supports with a span of 10 millimeters. This span length was chosen to represent the typical distance between brackets in the anterior and premolar regions where initial leveling and alignment forces are applied. A centrally positioned stainless steel plunger with a 0.5 millimeter radius tip was used to deflect the wire at the midpoint between the supports. The crosshead speed was set to 1.0 millimeter per minute, a rate selected to approximate the relatively slow rate of force application encountered during clinical wire engagement while allowing for accurate data acquisition.

Each specimen was loaded to a maximum deflection of 3.1 millimeters and subsequently unloaded to zero. This deflection range was selected to represent the range of activations typically encountered during clinical archwire placement, where the wire is engaged into brackets from a passive state to deliver forces for tooth movement. Load values in Newtons were recorded at specific deflection intervals of 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 millimeters during both the loading and unloading phases. These intervals provide detailed force-deflection curves that characterize both the activation forces, delivered during wire engagement, and the deactivation forces, which represent the forces delivered to the teeth as the wire returns toward its passive state.

Statistical Analysis

Data were analyzed using statistical software, version 25.0. Descriptive statistics, including means and standard deviations, were calculated for the load at each deflection point for all three experimental groups. These summary statistics provide an overview of the central tendency and variability of the load measurements within each group.

A one-way analysis of variance was employed to identify significant differences in load values between the three groups at each deflection interval. This test compares the variance between group means to the variance within groups, providing a statistical assessment of whether the observed differences are likely to represent true differences rather than random variation. Following the analysis of variance, Tukey post-hoc test was applied to perform pairwise comparisons between groups, identifying which specific groups differed significantly from one another. The post-hoc test adjusts for the increased risk of Type I error associated with multiple comparisons.

The significance level was set at $p < 0.05$ for all statistical tests, representing a 5% probability of incorrectly rejecting the null hypothesis of no difference between groups. This threshold is consistent with standard practice in dental materials research and provides a balance between sensitivity for detecting clinically relevant differences and protection against false-positive findings.

Results

The load-deflection curves for all three groups exhibited the characteristic superelastic behavior of Nickel-Titanium archwires, consisting of an initial elastic phase, a loading plateau corresponding to the stress-induced transformation from austenite to martensite, and an unloading plateau corresponding to the reverse transformation from martensite back to austenite. This typical force-deflection pattern confirms that all specimens, regardless of their experimental condition, retained the fundamental phase transformation behavior that underlies the clinical utility of these archwires. However, quantitative differences in the loading and unloading forces, as well as in the shape of the plateaus, were observed among the groups, indicating that intraoral exposure and sterilization altered the mechanical response of the material.

Loading Phase Characteristics

The mean forces recorded during the loading phase at various deflection points are presented in Table 1. Loading forces represent the resistance encountered during engagement of the archwire into brackets, reflecting the combined contributions of the material's stiffness and its phase transformation behavior under increasing stress.

At the maximum deflection of 3.0 millimeters, Group 1, the as-received control group, exhibited a mean loading force of 4.32 ± 0.18 Newtons. This value represents the baseline force required to achieve this degree of deflection in an unexposed archwire. Group 2, consisting of wires retrieved after 4 weeks of clinical use, showed a higher mean loading force of 4.58 ± 0.22 Newtons at the same deflection point. Group 3, comprising retrieved wires that were subsequently subjected to steam sterilization, demonstrated the highest mean loading force of 4.65 ± 0.25 Newtons.

The trend of increasing loading forces across the experimental groups suggests that both intraoral exposure alone and the combination of intraoral exposure with sterilization altered the mechanical behavior of the archwires, requiring greater force to achieve the same degree of deflection. Statistical analysis revealed a significant increase in the force required to reach 3.0 millimeters of deflection in the retrieved and sterilized groups compared to the control, with p-values less than 0.05. This increase was progressive, with Group 3 showing the highest loading forces, followed by Group 2, and Group 1 demonstrating the lowest loading forces.

Table 1: Mean loading forces (N) at specific deflection points (Mean ± SD)

Deflection (mm)	Group 1 (Control)	Group 2 (Retrieved)	Group 3 (Retrieved + Sterilized)
0.5	1.82 ± 0.12	1.94 ± 0.15	1.98 ± 0.14
1.0	2.95 ± 0.14	3.12 ± 0.18	3.18 ± 0.20
1.5	3.42 ± 0.11	3.65 ± 0.19	3.72 ± 0.21
2.0	3.88 ± 0.15	4.10 ± 0.22	4.18 ± 0.24
2.5	4.15 ± 0.16	4.38 ± 0.20	4.45 ± 0.23
3.0	4.32 ± 0.18	4.58 ± 0.22	4.65 ± 0.25

Unloading Phase Characteristics

The unloading plateau represents the clinical force delivered to the teeth during archwire deactivation, which is the primary determinant of the biomechanical response of the periodontium to orthodontic loading. The unloading phase data, presented in Table 2, revealed distinct variations among the groups that have important clinical implications.

At 2.0 millimeters of deflection, a point within the typical unloading plateau range, Group 1 demonstrated a mean unloading force of 1.42 ± 0.09 Newtons. This value represents the baseline force delivered by as-received archwires at this degree of deactivation. Group 2 exhibited a significant reduction in unloading force to 1.25 ± 0.11 Newtons at the same deflection point, representing a decrease of approximately 12% relative to the control. Group 3 showed a further reduction to 1.18 ± 0.13 Newtons, representing a decrease of approximately 17% relative to the control.

The reduction in unloading forces was evident across the entire range of deflection points measured, from 3.0 millimeters down to 0.5 millimeters. At 3.0 millimeters of deflection, Group 1 demonstrated an unloading force of 2.45 ± 0.14 Newtons, compared to 2.32 ± 0.18 Newtons in Group 2 and 2.25 ± 0.20 Newtons in Group 3. At lower deflections, the differences between groups became proportionally more pronounced relative to the absolute force values.

Table 2: Mean unloading forces (N) at specific deflection points (Mean ± SD)

Deflection (mm)	Group 1 (Control)	Group 2 (Retrieved)	Group 3 (Retrieved + Sterilized)
3.0	2.45 ± 0.14	2.32 ± 0.18	2.25 ± 0.20
2.5	1.68 ± 0.10	1.48 ± 0.12	1.42 ± 0.15
2.0	1.42 ± 0.09	1.25 ± 0.11	1.18 ± 0.13
1.5	1.38 ± 0.08	1.21 ± 0.10	1.14 ± 0.12
1.0	1.32 ± 0.07	1.15 ± 0.09	1.08 ± 0.11
0.5	0.75 ± 0.12	0.62 ± 0.14	0.58 ± 0.15

The force gap, representing the hysteresis between the loading and unloading curves, was significantly wider in the retrieved and sterilized groups compared to the as-received controls, with statistical significance at $p < 0.01$. The widening of the hysteresis indicates that the energy dissipation characteristics of the archwires were altered by both clinical use and the sterilization process, with the combination of both factors producing the most pronounced effect.

Permanent Deformation

Visual inspection of the archwires following the completion of the load-deflection cycle revealed differences in the incidence of permanent deformation among the groups. No visible permanent deformation was observed in any of the control group specimens after testing, indicating that the as-received archwires fully recovered their original shape upon unloading, consistent with ideal superelastic behavior.

In contrast, 3 out of 15 wires in Group 2, representing 20% of the retrieved group, exhibited minor permanent sets characterized by residual deflection greater than 0.1 millimeters upon completion of the unloading cycle. Among Group 3, 5 out of 15 wires, representing 33% of the retrieved and sterilized group, demonstrated permanent deformation. The increasing incidence of permanent deformation across the groups suggests that both intraoral exposure alone and the combination of intraoral exposure with sterilization reduced the ability of the archwires to fully recover their original shape following mechanical loading. The observation that the sterilized group showed a higher incidence of permanent deformation than the retrieved group indicates that the sterilization process contributed additional degradation of the material's shape recovery properties beyond that caused by clinical use alone.

Discussion

The results of this study indicate that both clinical use and subsequent steam sterilization significantly alter the load-deflection characteristics of superelastic Nickel-Titanium archwires, challenging the assumption that reprocessed archwires maintain mechanical properties comparable to as-received materials. The most notable findings were the increase in loading forces and the concomitant decrease in unloading plateau forces in retrieved and sterilized specimens compared to the as-received controls. These changes result in an increased hysteresis, which has direct implications for the efficiency of orthodontic tooth movement and the predictability of clinical outcomes [1, 2].

The increase in loading force observed in Groups 2 and 3 suggests that both intraoral exposure alone and the combination of intraoral exposure with sterilization alter the mechanical behavior of the archwires during activation. During the 4-week clinical period, archwires are subjected to a complex array of mechanical and environmental challenges. Masticatory forces impose cyclic loading that can induce microstructural changes within the alloy, while the movement of the wire within bracket slots generates friction and wear at the interface. Research has shown that even brief clinical exposure can lead to surface pitting, corrosion, and the accumulation of an integument consisting of salivary proteins, microbial biofilm, and mineralized deposits [3]. This surface roughening increases the coefficient of friction between the wire and the bracket, requiring higher initial forces to achieve a specified deflection. Additionally, the mechanical cycling associated with mastication and occlusal contacts may induce work hardening of the alloy, resulting in an increased resistance to deformation that manifests as higher loading forces.

The significant reduction in the unloading plateau force, which represents the active force delivered to the teeth during tooth movement, highlights a loss of the wire's superelastic efficiency. In this study, the unloading force at 2.0 millimeters of deflection dropped from 1.42 Newtons in the control group to 1.25 Newtons in the retrieved group and further to 1.18 Newtons in the sterilized group. This reduction can be attributed to degradation of the alloy's internal crystalline structure and its ability to undergo the reversible phase transformation that underlies superelastic behavior. Previous studies have suggested that the oral environment promotes hydrogen absorption into the Nickel-Titanium lattice, a phenomenon known as hydrogen embrittlement, which can interfere with the reversible phase transformation between austenite and martensite [5, 6]. When hydrogen atoms occupy interstitial sites within the crystal lattice, they impede the movement of dislocations and interfere with the coordinated atomic shifts required for phase transformation. When the transformation is hindered, the stress-induced martensite does not fully or efficiently revert to austenite upon unloading, leading to lower force delivery and the occasional permanent deformation observed in this study [7].

The addition of steam sterilization in Group 3 appeared to exacerbate these mechanical changes, further reducing unloading forces and increasing the incidence of permanent deformation. The thermal energy provided during the 134°C autoclave cycle may act as a low-temperature aging process that induces additional microstructural modifications [8]. It has been documented that repeated thermal cycling can lead to the precipitation of nickel-rich phases within the alloy, which alters the transformation temperatures, particularly the austenite finish temperature, and modifies the plateau stress levels [9, 10]. The precipitation of secondary phases creates internal strain fields that impede the movement of phase boundaries during transformation, reducing the efficiency of the shape recovery mechanism. Our data suggests that while sterilization alone may not render a wire clinically unusable, the cumulative effect of biological aging during intraoral exposure and subsequent thermal processing reduces the predictability of the force system [11].

The observed reduction in unloading forces has direct clinical implications for orthodontic treatment. The 12% reduction in unloading force observed in the retrieved group and the 17% reduction observed in the sterilized group may lead to suboptimal tooth movement or extended treatment times. Orthodontists rely on the constant force property of superelastic Nickel-Titanium archwires to deliver forces within a therapeutic window that promotes efficient tooth movement while minimizing patient discomfort and adverse tissue responses. When reprocessed wires deliver forces below the biological threshold required for efficient remodeling of the alveolar bone, the rate of tooth movement may be reduced, potentially prolonging the leveling and aligning phase of treatment [12]. Conversely, the increased loading forces required to engage reprocessed wires may increase chairside time and patient discomfort during archwire placement.

The increased incidence of permanent set observed in the recycled groups, with 20% of retrieved wires and 33% of sterilized wires exhibiting residual deformation, suggests a loss of shape memory that may compromise the final alignment quality during the leveling phase. The ability of superelastic archwires to return to their original shape upon unloading is essential for maintaining consistent force delivery throughout the activation range. When permanent deformation occurs, the wire may not fully engage the brackets or may exert unpredictable force vectors, potentially compromising treatment outcomes [13].

Limitations of the current study include the relatively short intraoral duration of 4 weeks, which represents a typical interval between orthodontic adjustments but may not capture the cumulative effects of longer-term exposure. Additionally, the study employed a single-cycle sterilization protocol, whereas in clinical practice, archwires intended for reuse might be subjected to multiple sterilization cycles. The use of a single sterilization cycle may underestimate the cumulative degradation that could occur with repeated reprocessing. The study was conducted under controlled laboratory conditions with standardized deflection parameters, which may not fully replicate the complex three-dimensional loading patterns encountered during clinical use. Furthermore, the mechanical testing was performed immediately following retrieval and sterilization, without simulating the additional storage or handling conditions that might occur in clinical practice.

Future research should investigate the long-term fatigue life of reprocessed archwires through cyclic loading protocols that better approximate the repeated stresses encountered during mastication and tooth movement. The impact of different sterilization methods, such as chemical vapor sterilization, dry heat sterilization, or ethylene oxide gas, on the crystalline stability and mechanical properties of Nickel-Titanium archwires warrants investigation, as these methods may induce less thermal stress on the alloy [14, 15]. Additionally, surface characterization studies using scanning electron microscopy and atomic force microscopy could provide insights into the microstructural and topographical changes underlying the observed alterations in mechanical behavior. The clinical implications of reprocessed archwire use should be evaluated through prospective clinical trials comparing treatment outcomes and duration between patients managed with new versus reprocessed archwires. Finally, the cost-effectiveness of archwire recycling must be weighed against the potential for compromised treatment efficiency and increased chairside time to determine whether the practice of archwire reprocessing is justified from both clinical and economic perspectives.

Conclusion

The findings of this study demonstrate that the clinical use and subsequent steam sterilization of superelastic Nickel-Titanium archwires lead to significant alterations in their mechanical performance. Specifically, the loading force required for activation increased, while the unloading plateau force—the critical force for orthodontic tooth movement—decreased significantly compared to as-received wires.

The increased hysteresis and the reduction in delivered force levels suggest that recycled archwires may not provide the same degree of clinical efficiency or predictability as new wires. Furthermore, the observation of minor permanent deformation in a subset of the retrieved and sterilized samples indicates a compromise in the alloy's shape memory properties.

While the economic and environmental benefits of recycling orthodontic materials are noteworthy, the observed 17% reduction in unloading force following clinical use and sterilization may delay treatment progress or result in sub-optimal biological responses. Clinicians should exercise caution when reusing NiTi archwires, as the cumulative effects of the oral environment and thermal processing can diminish the unique superelastic advantages that these materials were designed to provide.

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